A MODEL BASED APPROACH FOR DETERMINING DATA QUALITY METRICS IN COMBUSTION PRESSURE MEASUREMENT

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A model based approach for determining data quality metrics in combustion pressure measurement

A study into a quantative based improvement in data quality

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Abstract

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Keywords: Combustion Measurement, Data Quality, Result Calculation, Simulation, Modelling, Error simulation, Combustion Pressure, Internal Combustion

This thesis details a process for the development of reliable metrics that could be used to assess the quality of combustion pressure measurement data - important data used in the development of internal combustion engines.

The approach that was employed in this study was a model based technique, in conjunction with a simulation environment - producing data based models from a number of strategically defined measurement points. A simulation environment was used to generate error data sets, from which models of calculated result responses were built. This data was then analysed to determine the results with the best response to error stimulation. The methodology developed allows a rapid prototyping phase where newly developed result calculations may be simulated, tested and evaluated quickly and efficiently.

Adopting these newly developed processes and procedures, allowed an effective evaluation of several groups of result classifications, with respect to the major sources of error encountered in typical combustion measurement procedures. In summary, the output gained from this work was that certain result groups could be stated as having an unreliable response to error simulation and could therefore be discounted quickly. These results were clearly identifiable from the data and hence, for the given errors, alternative methods to identify the error sources are proposed within this thesis.

However, other results had a predictable response to certain error stimuli, hence; it was feasible to state the possibility of using these results in data quality assessment, or at least establishing any boundaries surrounding their application for this usage. Interactions in responses were also clearly visible using the model based sensitivity analysis as proposed. The output of this work provides a solid foundation of information from which further work and investigation would be feasible, in order to achieve an ultimate goal of a full set of metrics from which combustion data quality could be accurately and objectively assessed.

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Glossary

°C	Degrees celsius
ADC	Analogue-to-digital converter
AEAP	Average exhaust absolute pressure
AFR	Air fuel ratio
ASCII	American standard code for information interchange
BDC	Bottom dead centre
CA	Crank angle
CA50	Crank angle of 50% conversion
CI	Compression ignition
CO2	Carbon dioxide
COV	Coefficient of variation
CPM	Combustion pressure measurement
DI	Direct injection
DOE	Design of experiment
DPF	Diesel particle filter
ECU	Electronic control unit
EEOC	Estimated end of combustion
EGR	Exhaust gas recirculation
FEAD	Front end auxiliary drive
FFT	Fast Fourier transform
FMEP	Friction mean effective pressure
HC	Hydrocarbons
HCCI	Homogeneous charge compression ignition
HP	High performance
IBDC	Inlet bottom dead centre
IFEM	Indicating front end module
IFILE	Indicating data file
IMEP	Indicated mean effective pressure
kB	Kilobyte
kHz	Kilohertz
kPa	Kilopascals
LogPV	Logarithmic pressure vs. volume
MB/Mbar	Millibar
MBF	Mass burned fraction
MEP	Mean effective pressure
MFB	Mass fraction burned
MHz	Megahertz
NA	Naturally aspirated
NLPCA	Non-linear principle component analysis
NO	Nitrogen oxide
NOx	Oxides of nitrogen
OBD	On-board diagnostic
PC	Personal computer
PCCI	Pre-mixed charge compression ignition

PM	Particle matter
p-V	Pressure vs. volume
RFB	Radius fraction burned
RHS	Right hand side
ROC	Ratio of compression
ROHR	Rate of heat release
RPM	Revolutions per minute
SI	Spark ignition
TDC	Top dead centre
USP	Unique selling proposition
VTG	Variable Turbine Geometry
WOT	Wide open throttle

1 Introduction

In a modern powertrain development environment, Engineers are chasing increasingly challenging targets, with contradicting requirements. In this environment good quality, reliable data is an absolute must. Some measurements can be easily quantified in terms of quality, and there is much literature supporting this. However, for combustion pressure measurement data – data quality are not as well defined. This could be due to the fact that this measurement is still seen as a specialist task. In addition, no real standards for combustion data (procedures, best practice, quality definition etc.) exist. Most often, all the information for best practice is held locally in a company and generally passed on in a ‘tribal’ way.

However, combustion pressure measurement is a necessary technique and the data is essential for engine development. More recently, the measurement task is carried out by less experienced persons and this is the main reason why a set of objective quality indicators for combustion measurement data could be very useful in the community of Engineers using this measurement technique. That is, to give a simple yes/no indicator, derived from quantitative analysis of the measured data, in order to give a reliable indicator for the user as to whether the data is useable, and if it is not, where the issue causing the error could be.

1.1 Overview of the thesis

In this thesis, the process of developing objective data quality metrics, derived from the pressure curve measured on reciprocating combustion engines, using a model based approach will be explored and documented.

Firstly, the background issues are examined and general statements regarding the cause and effects of variation in data quality in this environment are made. In addition, the value of having key performance indicators that directly relate to the ‘quality’ of the data for further analysis is justified and stated.

The literature relating to typical result calculations and evaluations is examined and explored in detail. In addition, existing literature on the subject of combustion pressure measurement best practice has been thoroughly researched, and salient points are stated and discussed. The published work and research in this area is critiqued as to the relevance and value, with respect to this investigation.

An overview of the theory relating to standard combustion measurement and analysis is explored. The most commonly used calculations, typically encountered in the combustion pressure analysis task are detailed and explored as to their reliability for general purpose tasks. Also, the boundary conditions which affect the applications of these calculated values are researched and explained.

The theory of developing the key performance metrics and the resulting analytical approach is explained and discussed; the novel model based approach applied to this task is described in full. In particular, the reasoning for using this method in the data generation and analysis phase in order to define metrics which were able to respond effectively to appropriate stimulation via fault simulation.

The experimental environment and test environment was a pivotal factor in the development of the metrics. An effective simulation environment that allowed rapid prototyping and testing of metrics, via fault simulation and an automated test process, are described in full. The modelling and approach, using a commercial tool is also explained fully.

Once key result metrics were identified, verification was necessary in a real-time, operational environment. A suitable test plan and methodology was developed and executed in order to verify and validate the experimental data gained previously.

The overall results and outcomes are described in detail, as to which metrics could be the most suitable and appropriate for combustion pressure measurement diagnostic use. The boundary conditions and limitations relating to the use of these metrics are discussed.

Finally, an overall statement is made as to the application of these metrics in a working environment. The real world use of such metrics in order to assist in measuring good quality combustion data is proposed. The commercial value of such objective data quality analysis via key metrics is mentioned and this is where the value to industry and research for this work can be appreciated fully. In addition, the value of further experimental work in this specific area is discussed and further research areas, relating to objective analysis of combustion pressure data quality, is explored and proposed.

1.2 Combustion pressure measurement (CPM)

Combustion pressure measurement, also known as Engine Indicating, is a technique used in the design, development and optimisation of reciprocating combustion engines.

The process of measuring the pressure inside the cylinder of a reciprocating piston engine dates back to the dawn of the development of reciprocating engines themselves. During the early development of the steam engines, an understanding of the in-cylinder process of energy release was fundamental to the optimising of the engine as a complete machine. The engine cycle operation can be visually represented via a diagram which plots instantaneous cylinder pressures against cylinder volume, these are known as 'Indicator' diagrams. The measurements are taken using a measuring device known as an Engine Indicator which is able to draw the diagram whilst the engine is running. The information gained from this measurement has many applications including use in improving efficiencies and optimising in-cylinder motion and expansion of the working fluids. At the time these measurements were undertaken and used by, amongst others, James Watt. Figure 1.1 shows a typical indicator diagram derived from early, simple equipment.

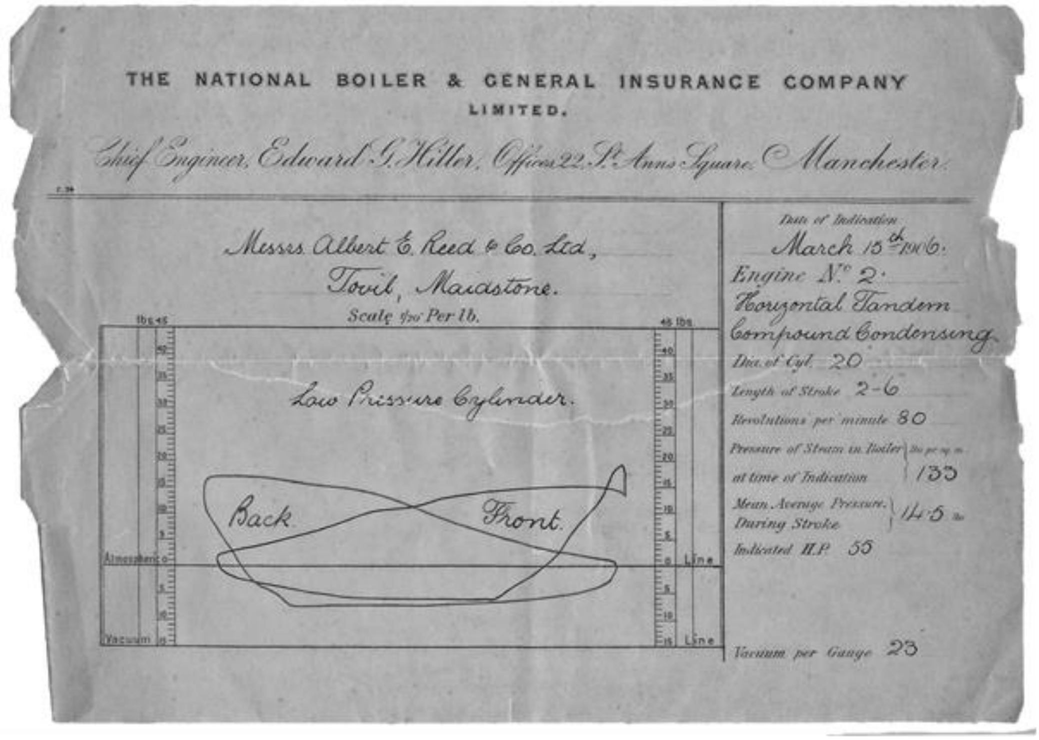


Figure 1.1: Indicator diagram derived from Steam Engine Drum type Indicator (source: John Walter – Archiving Industry)

These devices, generally known as 'Indicators', were installed at the engine, so that they were subjected to the working pressure in the cylinder. In addition, they were connected to the engine crosshead or crankshaft - from these two fundamental measurement inputs (pressure and, volume derived from the crankshaft/crosshead position) the characteristic loop of the pressure/work cycle could be measured and recorded for analysis.

Today, combustion pressure data is normally acquired with a measurement chain that is optimised for this task. Pressure is measured via an in-cylinder mounted transducer; the raw signal is conditioned, digitally sampled and processed in the data acquisition device. Cylinder volume must also be determined in conjunction with the pressure; this is normally derived by measuring the engine angular position via an encoder. The two signals are combined in software to give a pressure versus crank angle trace, from which further processing and calculations are made to provide the user with the results by which he can establish combustion quality and efficiency. The measurement hardware for the data acquisition has to support the high temperatures and pressures found in the cylinder, as well as having high immunity to interference from noise and vibration. Figure 1.2 shows a very early style of moving tablet indicator. Figure 1.3 shows a typical modern device, integrated into a test system cabinet.

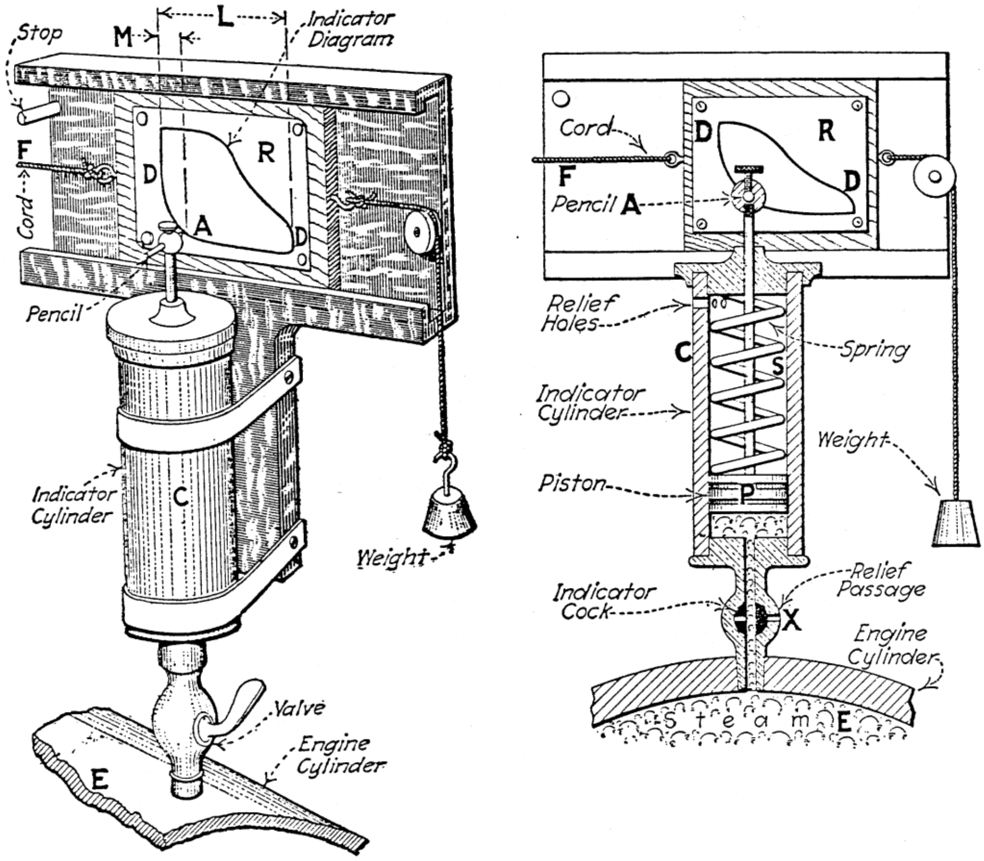


Figure 1.2: Moving Tablet Type Indicator circa 1790's (source: John Walter – Archiving Industry)

Figure 1.3: A modern Indicator system installed at a test bed for combustion pressure analysis (source: AVL)

The most prominent characteristic feature of all true digital Indication measurement devices is the ability to capture the data in the angular domain. Data is sampled at high frequency (up to 1MHz) and digitised but the trigger for each sample is the angular crank degree marks. Hence, it is possible to sample the data at a constant rate with respect to crank angle position but with a variable frequency matched exactly to the engine speed. An overview schematic of a typical digital system and components is shown in Figure 1.4.

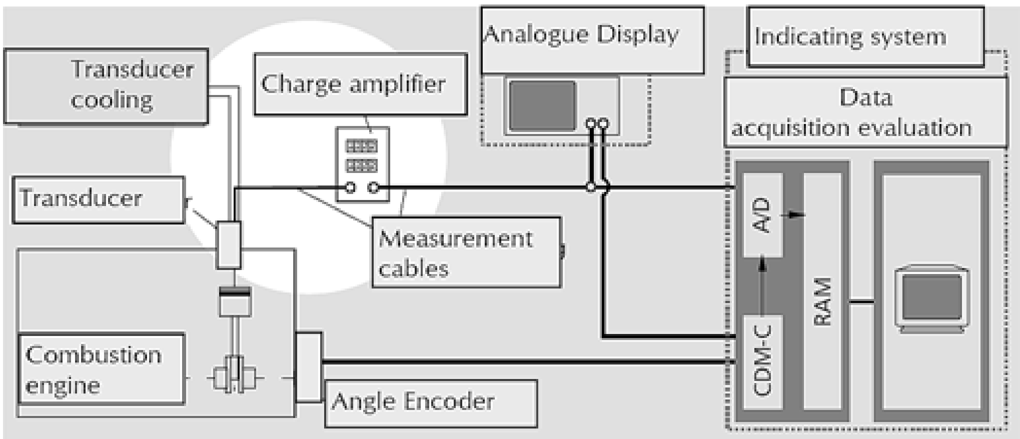
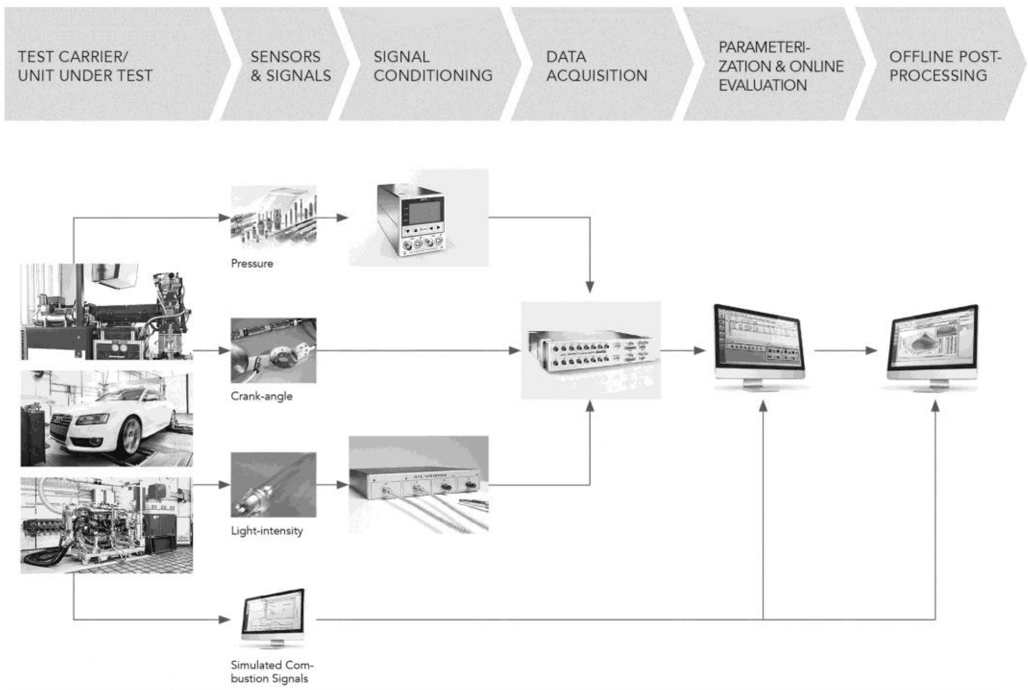


Figure 1.4: Overview diagram of a digital indication system (source: AVL)

1.3 Typical measurement system and process

A typical modern combustion measurement system consists of a number of component areas that are integrated together to form the complete measurement chain. The process of measuring and analysing combustion pressure data occurs in a number of steps related to each component of the measurement chain. The force applied to the measuring element in the sensor by the cylinder pressure must be converted into an electrical signal of sufficient amplitude than can be recorded, digitised and stored, ready for digital processing. After this, the required parameters of interest can be derived or calculated from the raw data. The conversion process is shown in Fig. 1.5 below.



ANALOGUE	DIGITAL

Figure 1.5: Conversion process of raw measurement data, through the combustion measurement chain (source: AVL)

Each step in the measurement process is summarised below:

The transducer – This converts the measured phenomena of interest into an electrical signal that can be conditioned. Various technologies are employed, according to the target of the measurement. For example, for cylinder pressure measurements, the most widely employed device is the piezo-electric pressure transducer. This employs a crystal measuring element that produces an electrostatic charge as a function of mechanical force. There are other technologies available for this task though, notably sensors with optical technology. For measuring other high-speed, engine related parameters or sub-systems, alternative sensor technology, for example, piezo-resistive, hall-effect and differential transformer principles are used in an appropriate sensor package to convert pressure or displacement into a suitable signal for further conditioning and measurement. A cross-section of a typical cooled type sensor is shown in Figure 1.6.

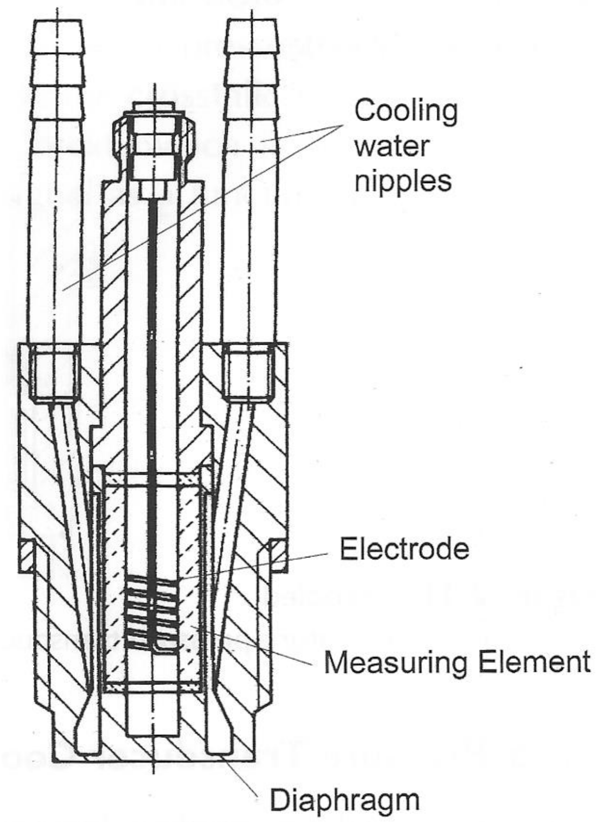


Figure 1.6: Cross section of cooled sensor (source: Kistler)

The signal conditioning (amplifier) – Once the transducer produces an electrical signal that is a linear or non-linear function of the measurement this signal must be conditioned to a suitable level for high-quality digitisation and processing by the data acquisition hardware. It is important the signal conditioning system does not introduce further interference or noise onto the amplified signal, in addition, any inherent phase shift could cause a serious error at the measurement system. These factors must be considered carefully. Included in the signal conditioning scope are the associated connecting cables, these are used to transmit the signals and they are a critical factor in providing high quality information along the measurement chain. A modern design of a compact, digital amplifier is shown in Figure 1.7 below.

Figure 1.7: Modern, compact charge amplifier module for piezo-electrical signals - AVL MicroIFEM (source: AVL)

The angle encoder – Most of the information derived from the pressure data curve is related to crank position or cylinder volume; hence, the source data must be established accordingly. In order to do this, an angle encoder must be fitted that provides degree of engine rotation sampling marks, at an appropriate resolution. In addition, the absolute position of the engine must be established, hence a once per rev or cycle mark must also be produced for a reference signal. An encoder arrangement for a front-end, engine mounting is shown in Figure 1.8. Note that for combustion measurement applications, it is imperative that the encoder is mounted to the crank using a rigid coupling method (in most engine speed/displacement measuring applications, a flexible coupling would be fitted to isolate the encoder from crank vibrations). The reason being, is that any flexibility between encoder and crank, will create unacceptable errors in the crank degree measuring table (due to vibration induced mis-alignment) under certain operating conditions.

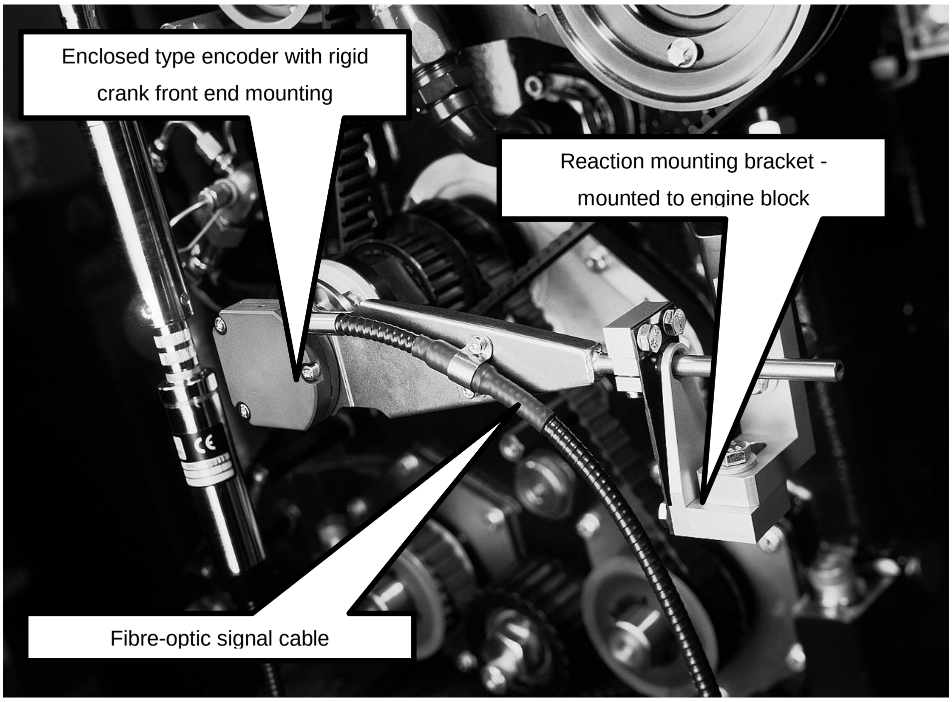


Figure 1.8: Angle Encoder system, rigidly mounted on Front Pulley (source: AVL)

Data acquisition system – This is where the two fundamental, required inputs (i.e. crank angle and cylinder pressure) are brought together to be processed, so that the parameters of interest can be calculated, displayed and stored for analysis. The voltage signal supplied by the signal conditioning system is digitised by the Data Acquisition System (sampling at crank degree intervals) where it can be subsequently stored in dynamic memory, generally, during this acquisition, the data is processed in real time so that the result data can be derived from the measured curves and displayed during run time of the measurement task. On completion of the measurement, the system allows the data to be transferred to a data file and stored permanently on a hard disk or file server. Often the system has a personal computer as a user interface, although this is not always true of older digital systems. A typical system layout and constellation is shown in Figure 1.9 below.

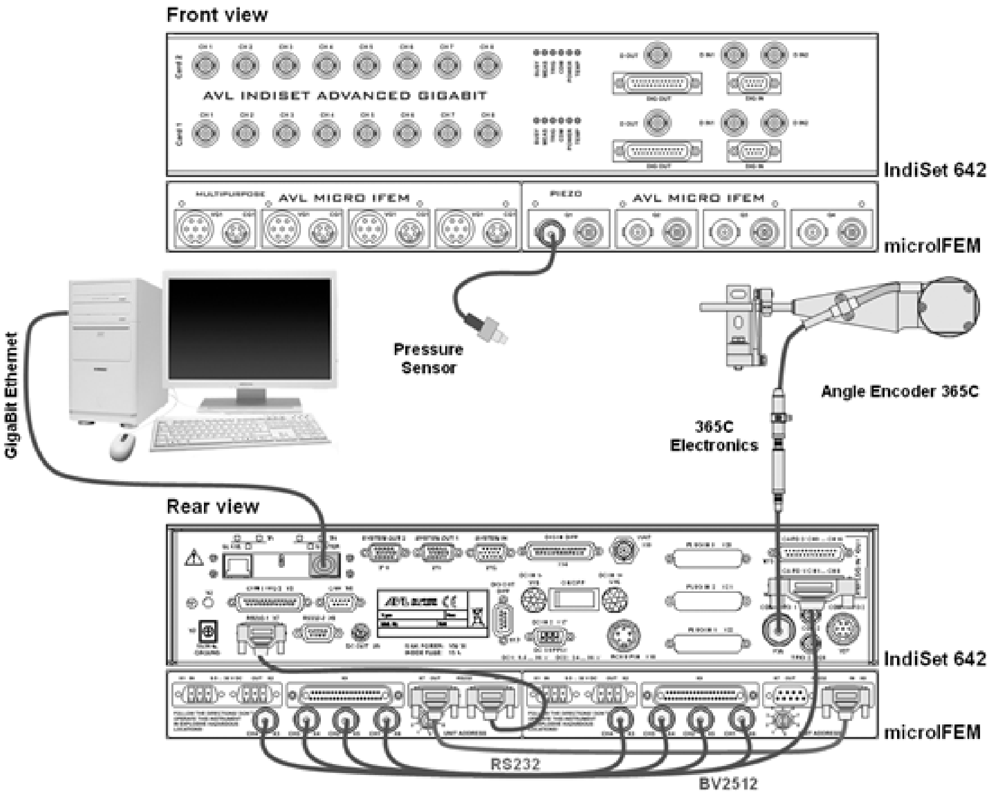


Figure 1.9: A typical Combustion system hardware measurement environment including data acquisition unit (source: AVL)

1.4 Importance of combustion pressure measurement data

Combustion analysis is a well-established method, used for many different purposes from calibration, to optimisation, base engine design and fuel research. Some typical applications include;

- Early engine combustion and fuelling concept development.
- Engine testing and development, from small portable to large stationary engines.
- Engine monitoring – large industrial engines may be equipped with crank based measurement and control systems.
- Control system development & calibration – nearly all modern engines have some form of electronic control. Combustion related data is essential for supporting optimisation targets, defining operational boundaries and calibration.
- Teaching and research – many of the interdependencies and trade-offs encountered in the physics relating to combustion engines can be illustrated with the use of combustion pressure measurements.

Crank angle based cylinder pressure data is essential to establish the performance and efficiency of the combustion engine, of particular interest is the measurement of pressure with respect to calculated volume. This allows the plotting of the Indicator Diagram, from which the term 'indicating' measurement is derived.

The combustion measurement system is a complex system that exists as part of the overall test environment, yet plays an essential role in understanding the engine behaviour for development and research purposes. The reason for this is that understanding the in-cylinder processes is so fundamental to the task of optimising the engine. Many measurement devices exist around the engine test bed, most of them measuring some fundamental input or output from the engine to ensure that it operated within limits, and to understand the engines consumption and output, for the purpose of increasing its efficiency and improving its performance. Most of these measuring systems are providing averaged, scalar result values or transient measured curves of fast sampled data points, depending on whether the main focus of the test is steady-state or transient operation of the engine.

The combustion measurement system is however quite different, the measurement data is sampled at high frequency (1 MHz), and is related to crankshaft position, producing cycle based curves of the measured channel against crank position. This is of interest as most of the engine processes and control subsystems are operating and controlling very fast processes, for example, initiation of the fuel burn process, which must occur in relation to the correct crank position. This data provides the fundamental understanding of the progress and quality of the combustion process that Engine Test Engineers and Scientists need.

1.5 Problem statement

The tools and technology available for this application have improved and developed considerably over the years with respect to capability. The performance of modern, digital data acquisition systems allows measurement and storage of combustion data, with online calculation and display of combustion related results and statistics, being available as a standard feature. Little prerequisite knowledge or expertise is needed to get a modern system up and running.

The combustion data itself is extremely sensitive to the quality of the measurement system set-up and parameterisation e.g. small errors can be multiplied during measurement run time, creating large errors in the raw data, and the derived results. These errors can be difficult, or even impossible, to discriminate and compensate for in data processing. This means that setting up and operating the system could still be considered a specialist task.

1.6 Aims and objectives

The aim of this work is to develop an environment, in order to research and create a set of metrics that can be used to assess the quality of a combustion pressure measurement data series.

The main objectives in this work are:

- To define a set of metrics for data quality analysis, that have suitable responses to the four main sources of error found in combustion measurement data, ideally, with two metrics for each error source.
- To create a rapid prototype development environment, where metrics can be developed and tested easily, without the need for physical testing in the early stages of development, using state of the art approaches and tools.
- To suggest how the metrics could be used individually, or in combination, to identify poor quality measurement data, from only a single engine cycle of pressure data.
- To be able to propose further direction of this work, with the ultimate goal of developing an automated detection environment, for use during measurement run time, or during post-processing, where poor quality data is identified objectively.

1.7 Contribution

This thesis details the development of an intelligent, model based approach that in this case, was employed effectively for the development of metrics for combustion data quality analysis. The overall aim of developing the data metrics for combustion data quality can be considered significant in this work due to the following main points:

- Reliable quality metrics will considerably help and support inexperienced users of combustion measurement equipment to be able to gauge if data is useable – either during run time or in post-processing. These metrics will provide useful information to support a detailed understanding of cause and effect, of typical error cases found in combustion pressure measurement tasks
- The use of a model based approach, in order to analyse data of this type, is uniquely applied in this work. It will also facilitate a detailed study into the interaction of typical combustion pressure result calculations.
- A prototyping environment, combining automation/simulation/model based testing and analysis will enable considerable efficiency gain (with respect to development time) during the development process – the method could also easily be applied in other domains for understanding reactions and interactions of variation and response groups.

1.8 Structure of the thesis

The main body of the thesis is as follows. Chapter 1 forms an introduction to the topic of combustion measurement, including descriptions of a typical measurement system and process, also the historical background of the technology. Main issues relating to measurement quality are discussed, this leads to a description of the aims, objectives and contribution of this work.

Chapter 2 is the literature review – an in-depth study of the directly relevant and peripheral literature, relating to combustion pressure measurement topics, with a particular focus on papers where data quality and best practice are topics. The main sources of error are grouped and discussed in order to develop solid background for the validity of the thesis.

In Chapter 3, the theoretical background of combustion measurement is explored. In particular the nature of some of the main sources of error, including their cause and effect. Additionally, the standard result calculations commonly used in combustion pressure measurement data analysis are reviewed with respect to theory and application.

Chapter 4 incorporates the main body of work in the study. In this section, the performance requirements of result metrics that will be developed within the study are defined. The development and simulation environment for prototyping result metrics is described. The novel approach of using design-of-experiments and modelling is explained in detail. Finally the automation and verification techniques used, in order to achieve high data quality, are discussed.

In Chapter 5 the results and analysis methodology is described. The verification data and procedure is examined, proving that the simulation environment developed was robust and reliable. The results gained from the model based environment were evaluated with respect to the application.

Chapter 6 forms a summary of the output from this work, the contribution of the work is defined, in addition, the processes used were evaluated reflectively and the key success highlighted. A conclusion section defines the next steps that could be taken for this work and provides recommendations for further work.

The overall thesis structure is shown in Figure 1.10 below:

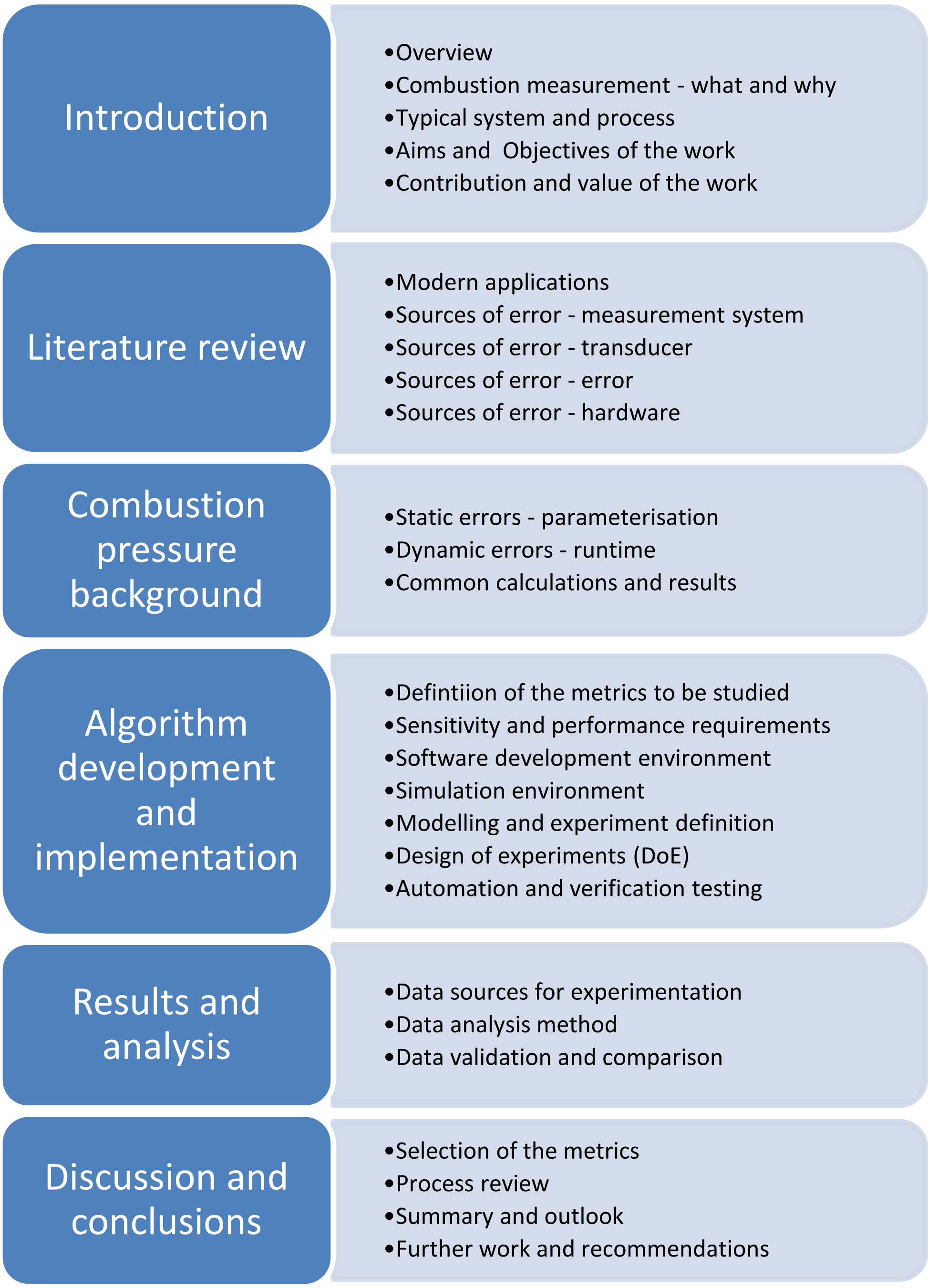


Figure 1.10: Thesis Structure

2 Literature review

Combustion pressure measurement is a decisive technique used in the development of internal combustion engines. Measuring and monitoring the cylinder pressure in relation to the instantaneous cylinder volume allows the engineer to gain a great deal of information about the quality and efficiency of the energy conversion process taking place inside the cylinder e.g. many useful metrics can be derived or extracted from the pressure curve, and these parameters are well known and used by experienced engine development scientists and engineers. Typical applications can include the combustion system and engine design aspects, right throughout the development process, from initial studies, through to final calibration and optimisation of the engine control system in the vehicle itself.

For combustion pressure measurement in reciprocating engines, the fundamental aspects of the system and its configuration are the most important with respect to achieving reliable measurement data. There is much published work on different aspects of the measurement chain components, and how to achieve an optimal set-up of these. In addition, there has been much research in the area of transducer technology, and the specific requirements relating to piezo-electric transducers.

2.1 Modern applications

Within the following section, literature is highlighted that showed a novel or alternative approach, with respect to aspects of combustion pressure measurement, data analysis or application.

2.1.1 Optimising calculation and data processing

With respect to normal measurement applications, Brunt et al. [1] proposed a novel method of data reduction that could be employed to reduce the volume of combustion measurement data in a typical environment. He compares the advantages of normally applied data reduction techniques; however, it is often the case that some fidelity of the data can be lost during reduction. This paper describes techniques for reducing the steady-state cylinder pressure data file size using variable crank angle resolution and assuming mean cycle characteristics are applicable over part of the engine cycle. This approach could reduce the data size to 10% of its original value. Brunt et al.. [1] made comparisons between the original and reduced pressure data reveal negligible differences in the pressure diagram and derived data. In current times though, since the publication of Brunt's [1] work, data storage volume issues are less relevant as generally, higher bandwidths and larger storage capacities are now lower cost and generally available. However, this work is valid in the context of 'big data' – that is, being able to reduce data such that making sense of it all is still viable.

Nagashima [2] proposed a new method for calculating IMEP that avoided the need for the numerical integration, and could thus be employed on simple micro-controller as used in series production engine control units. The need for this was stated as the trend towards direct injection engines and the need to closely control combustion in order to achieve development targets. The approach employed the use of a Fourier series to express the cylinder pressure diagram. It was claimed that this approach could achieve greater accuracy with fewer data points. Also, performance of the algorithm under transient operation conditions was stated as good. However, the algorithm still relies on good quality, accurately phased pressure data. So for on-board (in-vehicle) applications, the encoder and sensor technology will still limit the mainstream adoption.

2.1.2 Sensing technology

There have been numerous approaches to derive cylinder pressure curve data via novel sensor technologies, or via inferring the information from other measurable values.

Mobley [3] carried out some work to propose non-intrusive methods of determining cylinder pressure data. The basis being a piezo-electric washer installed under a cylinder head bolt. This would be subjected to the load variations caused by the change in cylinder pressure in the engine cylinder, and could reproduce this as a change in charge signal, this signal correlated quite well with the measured pressure signal but the experimental boundaries were too limited to be able to claim a really conclusive result. Also, no estimation of error was suggested in this paper. It is a promising direction but one that would need further work.

Optical based sensors have been developed and shown successfully in many applications – Ulrich et al. [4] and Roth et al. [5] have made detailed comparisons between optical sensors and piezo-electric sensors. In summary, the results were promising, but inconclusive. It could be stated that the optical sensor could have some advantages, but not enough to really displace the mainstream piezo-electric technology, known and trusted for many years. This is concurred with the market trends - in that the optical technology has not made any real impact in the market for combustion sensors yet.

Yamamoto et al. [6] proposed a cost effective sensing technology as an alternative to piezo-electric with a view to the series production market. The sensor element employed a Polycrystalline element (which is cheap to produce but has the undesirable property of large changes in sensitivity with respect to temperature). The sensor itself was fitted between the cylinder head and spark plug, in an adaptor arrangement. In order to compensate for large sensitivity change characteristic, Yamamoto et al. [6] developed an adaptive calculation, for real-time execution, to adapt sensitivity changes. In order to calibrate the system, a calculated motored curve was used to define gain and offset values in order to then calibrate the real pressure curve during runtime. The main applications studied were for abnormal combustion (knock, misfire).

Ion current methods of establishing in-cylinder pressure, for the purposes of knock control are mainstream technology and this is employed in certain production vehicles. However, Shimasaki et al. [7] explored this technique for measuring cylinder pressure for the purposes of accurate control and calibration of the engine controller during run time – in high-performance applications. The main areas of interest were abnormal combustion modes – knock and misfire detection but it was stated that future developments would be closed-loop cylinder pressure based control for detailed monitoring of the combustion status in order to more precisely and minutely control the engine operation and efficiency.

It is worthwhile to note that combustion pressure measurement combined with closed loop combustion control has been introduced into the market and made possible by non-intrusive sensing technology. General Motors have introduced the concept on a production, diesel engine passenger vehicle, utilising piezo-resistive sensing technology, incorporated into pre-heating glow plugs. The requirements for this sensor are quite different when compared to the needs of a sensor for use in development applications – the robustness and durability of the sensor are equally, or more important, than the sensor accuracy. The manufacturer (Beru) compared three main sensing technologies (optical, piezo-electric and piezo-resistive) for the application and concluded that piezo-resistive was the most suitable. The measurement is derived from a movable heating element, in connection with a metal bellow as sealing and equalization element. The combustion pressure present at the heating element/bellows produces a force component in the direction of the sensor element which is remotely mounted at the top of the sensor body. The deformation of the measuring diaphragm is recorded by the sensor element as a value that changes proportionally with the combustion pressure, and is evaluated by the internal sensor electronics.

2.1.3 Virtual, model and estimation based methods

There has been considerable research in the area of virtual or model based methods in order to be able to gain combustion related parameters for control and optimisation purposes. This approach is extensively employed in modern powertrain control units, where virtual sensors are very commonly used to characterise important parameters, without actually having a direct measurement – specific examples are for exhaust temperature, cylinder air charge and after treatment system status (loading).

Wang et al. [8] reiterated that the cylinder pressure signal for engine combustion control is highly desirable, particularly for advanced combustion modes under development (e.g. HCCI – Homogeneous Charge Compression Ignition). Also, that physical cylinder pressure sensing is too expensive for series production applications. Wang et al. [8] suggest an approach with two neural network-based independent cylinder pressure related variable estimators. These were developed and verified at steady state. The results shown demonstrated that these models can predict the variables correctly, compared with the extracted variables from the measured physical cylinder pressure sensor signal.

This virtual approach provided a solution that could be integrated into an engine controller (with the typical computing resources available in such a unit). It should be noted however that this research was limited to steady state conditions. The research clearly mentioned the fact that for the virtual sensors to work in the transient conditions, a high-order neural network with input delay components would be required.

Maass et al. [9] proposed another approach to virtual cylinder pressure measurement. The research [9] presents a new approach of in-cylinder condition prediction. Rather than reconstructing in-cylinder pressure signals from vibration transferred signals through cylinder heads or rods, this approach predicted the conditions using artificial, neural networks. Maass et al. [9] stated that the problem with indirect measurements approaches, is that they rely on the fact that the reconstruction of the in-cylinder conditions rely on transfer of pressure induced forces through engine components. Problematic with this approach is additional perturbations through engine operation such as piston slap, valve impacts or noise introduced through the structural signal transfer.

In this work [9], the key parameters for modelling of in-cylinder pressure are identified as inputs and a network structure was trained with data generated from a validated engine model. The resulting network can be used either for controller design, or in case of available measurements, for input as an on-board monitoring and diagnostic tool. The overall approach in this paper was promising, and could be useable in certain circumstances. However, the computing power needed to run a neural-network in real time, to predict combustion parameters for performance or diagnostic monitoring would currently not be available outside a research or prototyping environment.

Corti et al. [10] considered the problem of crank angle measurement in his work. The objective was to create a system, able to process in-cylinder pressure signals in the angular domain, without the need for a high-resolution crankshaft encoder. Thus, being able to use as an angular reference, the signal coming from a standard equipment sensor wheel (typically marks a 6 degrees crank angle). The approach used was to employ a high sample rate on a time base for the angle mark signal (10MHz) performing the transformation from the time domain to the angular domain by means of an interpolation algorithm.

Corti et al. [10] suggests that there are certain risks to accuracy in this conversion process. However, the work showed how these considerations can be taken into account in the implementation of the algorithm of IMEP and Heat release. In order to do this some parameters needed to be identified: the position sensor delay, the TDC actual position and the sensor wheel teeth unevenness. Algorithms implementing these functions were integrated within the main application developed.

This project [10] showed promising results, and methods were described of how to overcome identifying the potential referencing errors, without the need to fit an angle encoder, even in the system identification phase. However this approach still seems to be more appropriate for the development phase, rather than a solution that could be used in production. It could however be very appropriately employed where in-vehicle measurement is needed, later in the vehicle development phase.

Willems et al. [11] investigated cylinder pressure based control for diesel applications, in conjunction with the development of virtual heat release and emissions sensors (block diagram overview shown in Figure 2.1) – with a view to improving control performance and emissions compliance. The pre-requisite was the cylinder pressure data would be available, and then from this, Particle Matter (PM) and Oxides of Nitrogen (NO_X) were estimated using a physically-based combustion model. It was suggested that currently, PM sensors are not commercially available. Therefore, a virtual PM emission sensor has great added value, especially for DPF (Diesel Particle Filter) control. Furthermore, the virtual NO_x sensor has a cost advantage i.e. NO_x sensors can be omitted or less expensive versions can be used which are less accurate and/or have slower response times.

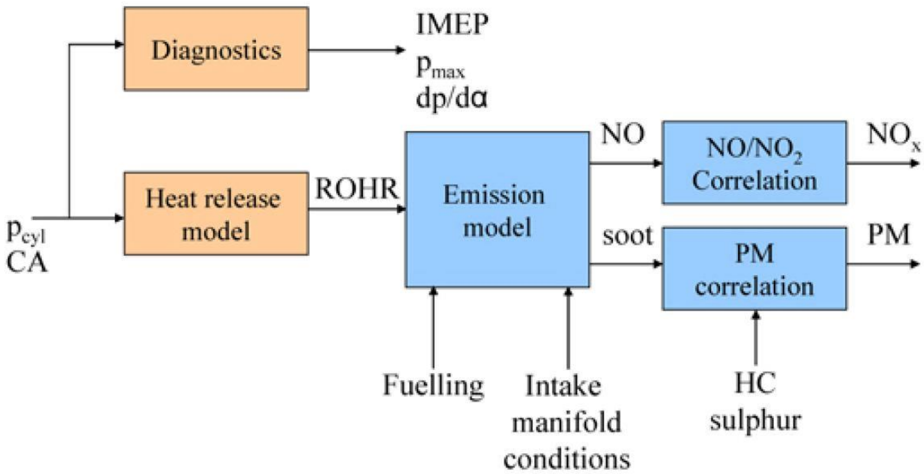


Figure 2.1: Block scheme of virtual heat release and emission sensor [11]

Performance of the heat release virtual sensor in this work [11], showed a capability of predicting the CA50 (Crank Angle of 50% conversion) with an absolute accuracy of 0.5 degree CA (Crank Angle). This level accuracy is of the same order as obtained for CA50 values derived from measured in-cylinder pressure data and is therefore, potentially sufficiently accurate for combustion phasing control. Using this virtual combustion pressure sensor in practice would mean important engine and after treatment control variables, such as the exhaust gas temperature, maximum in-cylinder pressure (rise) and specific fuel consumption could be expected to be predicted with a relative accuracy of ≤ 4%. This level of accuracy validated the use of the sensor in model-based control applications.

The virtual NO_x and PM sensors were successfully implemented for real-time control of engine-out emissions. For certain stated experimental conditions, the NO_x prediction accuracy was shown to be comparable with commercially available NOx sensors. For PM emissions, it was stated that only the qualitative accuracy is achievable - that is, the virtual emission sensor could capture the sensitivity of PM emissions with respect to important operating variables, such as injection timing and EGR rate. Although, in the experimental work, for injection timing sweeps, only two different operating points were studied, with fixed VTG (Variable Turbine Geometry) and EGR

(Exhaust Gas Recirculation) valve positions. For absolute levels of accuracy, performance was compromised – with values deviating between 2%, up to a factor of 2 from measured values. It was concluded that accurate DPF soot loading and emission control is not possible yet. Although absolute accuracy would be expected to increase when more detailed information on individual cylinder fuelling rates was available for utilisation in the model.

In common with much of the literature, no statement was made about the practical implementation or pre-requisites required to execute this algorithm in real-time, and what platform would be needed for this!

2.1.4 Condition monitoring

There are numerous studies on condition monitoring applications, which are relevant in the scope of this work. Various approaches to this topic have been researched with respect to Automotive and Powertrain applications. In addition, much work has been done in other industries, where the general principles and outcomes can be ported and re-used within Automotive Engineering domains. In this study the use of a model based approach for defining quality based metrics for combustion measurement data is proposed. Although this has not been covered specifically in any existing literature, some of the existing work can be considered in the context of this thesis, and similar principles can be applied and discussed here.

Grill et al. [12] presented a general hypothesis on the trend of data acquisition and distribution via telematics in the automotive field. It was suggested that diagnostic data, retrieved remotely, could be used to develop predictive algorithms. As opposed to current systems, where diagnostic algorithms are derived from expert and system knowledge, thus forming part of the system development process. It was stated that the major challenge would be how to really utilise the data mass, to provide understanding beyond classical diagnostics. Since this work was published there have been developments in the areas of ‘big data’ concepts (mainly internet based technologies) – this is an interesting area that could be very appropriately applied for this application.

Kim et al. [13] studied another area within the scope of condition monitoring. On board diagnostic functions use considerable resources within a control unit micro-controller. The focus of this work was to develop a misfire detection algorithm, with a much reduced processing burden. The principle being that the algorithm was only activated when the probability of misfire was high. This was successfully demonstrated using a statistically generated, pre-index. The work showed a reduction in processing time of a factor of seven, it was successfully applied and demonstrated in a rapid-prototyping environment.

McDowell et al. [14] proposed in general, the state of the art methods employed for condition monitoring and diagnostics. At the time of writing, it was suggested that a typical engine ECU has a processor speed of 50 MHz with 256 or 512 Kb of memory. With the increasing OBD (On Board Diagnostic) requirements, the ECU has to control the engine and also perform the necessary diagnostic algorithms. In general it is suggested that OBD requirements load the processor by approximately 50%. Due to microprocessor speed limitations, simple algorithms have to be employed to allow the diagnostic routines to be run in real-time.

It was stated that, in essence, the type of diagnostic used depends on the complexity of the system under supervision. Common strategies employed are:

- Model Based – deviations between a theoretical model and the physical process are used to determine fault conditions.
- Knowledge Based – prior knowledge of the physical process is used to ascertain when a fault condition has occurred.
- Signal Based – the signal is analysed or filtered to yield further information regarding the detection of faults.
- Data Based – a neural network can be used to train a ‘black box’ process model, without having a detailed understanding of the physical processes involved and then this is used to compare against the actual physical process

This work [14] suggested that model based approaches could be employed in diagnostics – to improve performance and reduce system loading – in particular the Non-Linear Principle Component Analysis (NLPCA). This technology is already proven in other industries (process and plant) and was successfully applied in this application (although offline). Advantages stated was time saving in developing the model, and the potential that reduced processing resources would be required compared to other methods. Implementing model based approaches in an engine controller requires a relatively high performance micro controller, not generally used yet in production – however, this work showed a promising approach for the future.

Some interesting work was done by Hines et al. [15] with respect to condition monitoring based on a single variable, for system health monitoring purposes. The basis of the work proposed was to monitor the frequency characteristics of a single sensed variable. The signal is transformed from the time domain to the frequency spectrum by taking the Fast Fourier Transform (FFT) of the temporal data, and the desired features of the frequency spectrum are extracted. It was suggested that system errors could be identified from features of the transformed data - peaks and valleys, or ratios thereof, which change in a significant way with faulted operation. The performance of the system gave a diagnostic accuracy of 96.3%. Further work was suggested in the paper, in particular, development of the prognostic model to accompany the single-variable monitoring system.

Dandge [16] proposed the need for and developed a simple condition monitoring system for engines not equipped with electronic controls. The system mainly focuses on monitoring of coolant temperature, alternator belt failure, and lubrication oil pressure and coolant level indication. The main driver for such a system would be in emerging markets – where automotive technology is less sophisticated – but the cost of failures can still be expensive with respect to cost and time.

Liu et al. [17] re-iterated the importance of cylinder pressure data for use engine control applications. The work presented proposed a comprehensive and practical technical solution for the estimation of the in-cylinder pressure from the crankshaft speed fluctuations, based on the crank shaft dynamic model. (A discrete-time rigid-body crankshaft dynamics model - based on the Kinetic energy theorem, as the basis expression for total torque estimation). The work showed a detailed and methodical approach, but the experiments also show that, as the engine speed increases, the crankshaft motion become more complicated - so that a multiple degree of freedom crankshaft model would be needed to further accurately model the crankshaft dynamics behaviour. In addition, the paper did not discuss in detail how this algorithm could be implemented in real time - with respect to what calculation resources would be needed, and in what environment was the target for implementation (research and development, production).

2.2 Sources of error in measurement

In common with many phenomena in the natural world, most of the problems come from specific areas, that is, 80% of the effects are derived from 20% of the causes – in common with the Pareto principle.

In combustion pressure measurement there are typically four categories of error source, these are;

- The measurement system (settings and parameters)
- The encoder system
- Measuring chain hardware (signal conditioning and cabling)
- The transducer

2.2.1 Errors relating to the measurement system

These errors are those which are relating the actual set-up and parameterisation of the measurement system – in advance of a measuring task. In particular - the so-called ‘static’ errors. These have a decisive effect on the quality of the raw data obtained, with respect to assignment of correct volume and the correct relationship between volume and pressure (phasing).

Lancaster et al. [18] suggests that volume assignment is a specific issue and accuracy of the measurement can be limited by the problems associated with accurate determination of cylinder TDC (Top Dead Centre) position. TDC can be established using measuring equipment (e.g. piston displacement sensors), these are generally well accepted as being able to provide an accurate TDC positioning value. Although Davis and Patterson [19] note that due to the fact that piston motion is not symmetric around TDC (due to pin offset), piston TDC and crank TDC can deviate depending upon the geometry. They also suggest that for results which are directly derived from the cylinder pressure curve, the accuracy of the encoder phasing (the TDC reference point) directly correlates to the accuracy of the calculated result; hence, for direct results small TDC errors are not so critical! However, Polytropic, IMEP (Indicated Mean Effective Pressure) and Heat Release calculations are significantly affected by TDC related errors.

Brunt [20] stated that angle phasing errors are known to produce large errors in the IMEP calculation - due to the high sensitivity of IMEP to crank angle phasing error, but the effect on MBF (Mass Burn Fraction) calculations is less well defined.

Amann [21] suggested that unless the association between TDC piston position and crank angle is established accurately, during quantitative analyses based on pressure and volume, data quality will suffer. For accurate determination of indicated mean effective pressure (IMEP), the phasing may have to be accurate within 0.1 crank-angle degree. He stated that a clue to incorrect phasing is provided when the compression and expansion lines cross on a logarithmic p-V diagram of motoring operation, this is a very often used visualisation to confirm correct phasing and is shown in Figure 2.2 below.

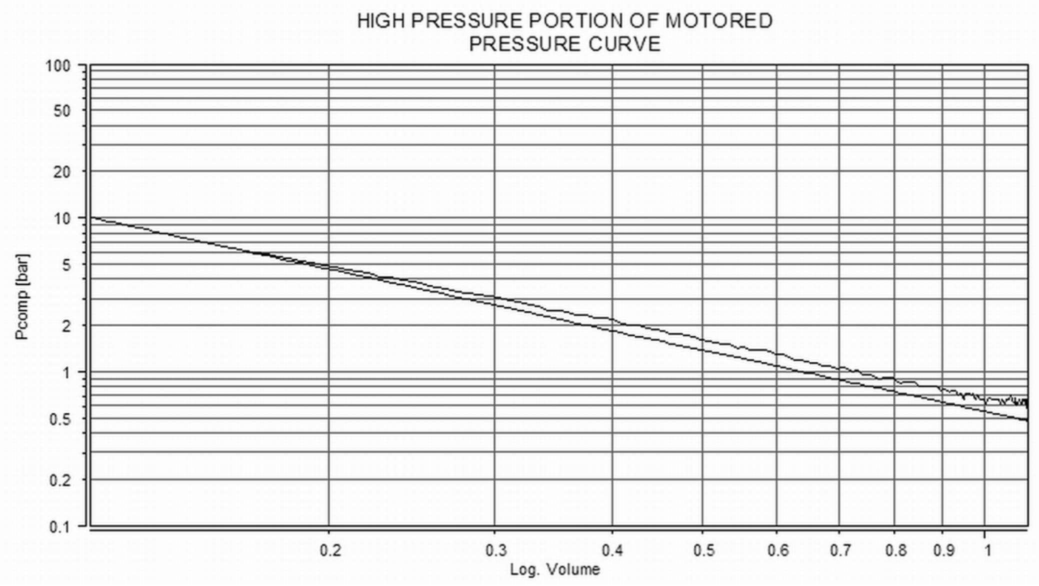


Figure 2.2: LogPV diagram of motored pressure

Amann [21] noted that merely inserting a dial indicator through the spark-plug hole and seeking the crank angle for highest piston position is unsatisfactory because of the insensitivity of crank angle to piston position near TDC. He stated it is better to take a series of dial indicator readings on either side of TDC) plotting them against crank position and fitting a least squares curve through the points. In a separate operation, the curve of piston position versus crank angle can be plotted from known engine geometry. Then the measured curve is overlaid on the geometric curve and shifted to minimize the difference, thus establishing the crank position that corresponds to TDC.

Amann [21] stated that if the phasing between piston position and crank angle is done correctly, then when the engine is motored, peak cylinder pressure will occur slightly before TDC because of cylinder heat loss and leakage. This check is easy to perform and is sufficiently sensitive that in one instance it revealed incorrect, reverse installation of a piston with offset. The angle by which peak pressure precedes TDC generally decreases with increasing engine speed and typically ranges from 0.7 to 0.9 degrees for spark-ignition passenger-car engines, 1.1 to 1.3 degrees for indirect-injection diesel engines, and 0.8 to 1.0 degrees for direct-injection truck diesels.

It is worthy to note and question the differences, basically it can be explained by the fact the loss angle is directly related to cylinder heat loss, this factor is relatively greater for compression ignition engines, where piston top land and surface area are typically larger than for a spark ignition engine

Kuratle et al. [22] concurred that for gasoline engines, TDC/Volume must be assigned to an accuracy of 0.1 degrees crank angle. Staś et al. [23] investigated and proposed a TDC determination method from pressure versus crank angle that follows the changes of the actual polytropic exponents at inflexion points during compression and expansion. Staś [23] suggested that erroneous TDC measurements, leading to incorrect phasing, are a major source of error in calculated results. IMEP error as a function of TDC (Phasing) error is plotted in the graph in Figure 2.3.

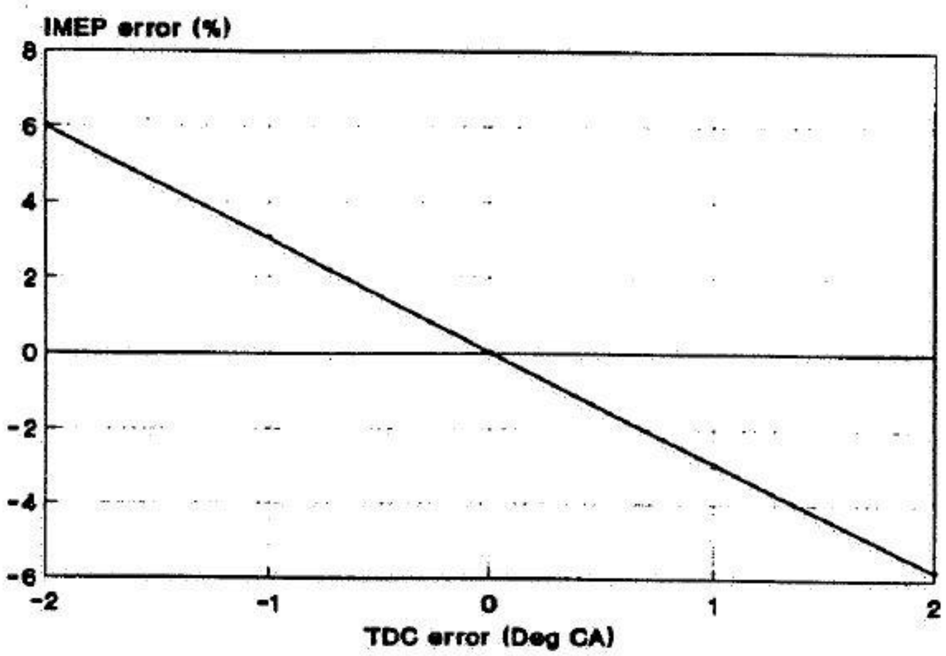


Figure 2.3: IMEP error as a function of TDC error [22]

Brown [24] observed that the error in IMEP is directly proportional to the error in the compression ratio definition for a motoring cycle.

Lancaster et al. [18] and Amann et al. [25] states when defining the compression ratio, the clearance volume establishment is accurate for moderate compression ratios, but liquid displacement should be used for high compression engines, even then, there will be some dynamic inaccuracies due to mechanical and thermal deformations during operation.

Lancaster [18] states that close observation of the compression line, derived from a Log Pressure-Volume plot can assist in identifying compression ratio errors via obvious curvature at the extremes.

Amann [21] noted that there is some variability in compression ratio from engine to engine, and in a given engine from cylinder to cylinder. The height of the compressed head gasket al.so has an influence on compression ratio that grows in significance as either compression ratio or bore/stroke ratio increase. Amann [21] stated that it is desirable therefore, to determine compression ratio after the engine is assembled.

Kuratle et al. [22] states that overall accuracy depends highly on correct definition of the ‘static’ parameters - crank drive geometry, compression ratio, as well as TDC accuracy.

Brunt et al. [26] stated that errors in the assumed compression ratio will cause discrepancies in the calculated cylinder volumes and hence errors in the calculated polytropic indices and MBF. These compression ratio errors can be experienced in practice as a result of manufacturing tolerances, or simply by specifying an incorrect value during parameterisation. The effect of compression ratio errors will be greatest on calculations performed close to TDC - where the greatest volume ratio errors are experienced.

Brunt [26] made a detailed analysis of potential errors sources with respect to heat release calculations – it was noted that incorrect definition of compression ratio is a common error when executing further calculations on the raw data.

Karim et al. [27] also made a similar analysis with respect to errors and heat release calculations; in particular, he stated that a 2% error in defining the compression ratio could lead to a 40% error in the calculation of gross heat release. He concluded that accuracy in defining the compression ratio is decisive for good quality measurement data!

An interesting development, for establishing compression ratio, for the purpose of condition monitoring was the subject of research carried out by Lamaris et al. [28] – He presented the evaluation of a diagnostic technique concerning its ability to estimate the operating condition and tuning of DI (direct injection) diesel engines. He used an engine simulation model for this purpose - Initially a two-zone model was used and this provided adequate results. However, this was further developed during the research to adapt for pollutant emissions of large diesel engines started and was thus modified and a multi-zone approach. The model input consists of vibration data and torsional vibration data. From this non-intrusive input data it was found that this technique can adequately provide the absolute value of the cylinder compression ratio – that can be adequately estimated without interrupting the fuel flow to the engine.

Randolph [29] suggests that accurate absolute cylinder pressure referencing is needed to achieve satisfactory values for derived parameters such as mass fraction burned, polytropic indices and charge temperature. Also that thermal shock compromises data in many respects. The necessary process of referencing the transducer output to a known pressure (known as referencing or pegging) introduces artificial variability into the pressure data, the severity of which depends on the pegging procedure used. Data accuracy deteriorates when cyclic variability is high at the time chosen to peg the transducer output. Because cyclic variability is increased by thermal shock, Randolph [29] suggests that it is best to peg during a portion of the cycle where transducer drift due to thermal effects is minimized.

Randolph [29] suggests several approaches to pegging/referencing – he stated that the referencing technique chosen can impact the cyclic variation of all engine parameters determined from absolute pressure.

Randolph [30] also suggests that with respect to data pegging/referencing. It is favourable to reference and adjust the pressure axis at inlet bottom dead centre, and this provided better results than pegging during the exhaust stroke or than pegging by forcing a polytropic compression. He noted though that the intake/exhaust design and part-load condition tested did not generate the dynamic pressure fluctuations existing in many production manifolds. These tuning considerations may degrade the accuracy (as opposed to the variability) of pegging during either the intake or exhaust strokes, in which case forcing a fixed polytropic coefficient would become the preferred procedure. Randolph [31] also mentions that with respect to high-performance engines, the challenges for correctly referencing the data are much greater – but, as some metrics do not need pegged data – it is acceptable to use an absolute sensor in the inlet manifold, or low in cylinder bore for correction purposes.

However, it should be noted that current state of the art engines are employing Miller cycling (over-expansion) in order to achieve development targets. These engine cycles could have an effect on the accuracy of the mentioned pegging methods, if these methods are used in certain engine operating conditions or modes. In particular, where valve timing events are used to vary cylinder filling and compression ratio (actual compression ratio as opposed to geometric compression ratio) – this is due to the pressure pulses that occur in the manifold due to the valve timing events. Also the fact that the pressure at BDC may not be atmospheric (for a NA engine).

Brunt et al. [20] experimented and quantified the effect of typical measurement errors, specifically with respect to the calculation of heat release and mass burn fractions (MBF). He compared a number of numerical approaches for the calculation of instantaneous energy release, noting the effect that typical errors have, and which algorithms are most sensitive. He noted that absolute pressure error, caused by incorrect pressure referencing, affected the calculated compression and expansion polytropic indices and can affect the calculated, estimated end of combustion (EEOC). Hence the mass fraction burned can be distorted by the pressure error, as well as the error due to the change in the signal itself.

Brunt [20] concluded his work by stating that MBF errors produced as a result of pressure data errors should be relatively small for well-designed algorithms. The highest sensitivity is to absolute pressure referencing errors, particularly at part load, and this sensitivity can be made worse by resulting errors produced in the calculated compression and expansion indices.

Brunt [32] suggests that pressure referencing errors are shown to produce large errors in derived parameters such as polytropic index; mass fraction burned and charge temperature. He also noted that pressure referencing errors can cause problems with detecting the end of combustion; a positive pressure offset giving a low polytropic index (as previously discussed) and producing the same effect as late combustion. Brunt [32] compared 2 common approaches to referencing – namely inlet manifold pressure and polytropic index (also known as the thermodynamic method). He stated that both pressure referencing methods have been shown to produce similar performance and are capable of accuracy better than +/-100 MB (millibar) (10kPa) under most conditions. He noted that very accurate pressure referencing is only possible when the pressure data are relatively free from measurement errors such as thermal shock, drift, noise and linearity deficiencies. Inlet manifold referencing is probably most accurate for the low pressure part of the cycle but is sensitive to linearity errors and most affected by thermal shock. Polytropic referencing should be better for combustion analysis but is more affected by signal noise and generally produces slightly higher cyclic variability.

Brunt et al. [20] also noted in other studies that for burn rate calculations – incorrect pressure referencing causes the greatest errors, especially at low load operating conditions.

Davis and Patterson [19] suggested that when setting the parameters for the referencing method, the selections of measurement point and transducer frequency response are critical.

Karim et al. [27] suggests that with respect to reference pressure pegging – the rate of heat release (ROHR) prior or post combustion are sensitive to pegging but that Integral heat release is not - as the errors cancel each other out.

Amann [21] mentioned that the simplest approach is to assume that at bottom dead centre on the compression stroke, when the intake valve is open and the piston is at rest, the cylinder pressure is equal to the average pressure in the intake manifold. He stated that this may result in an error in absolute pressure on the order of 10 kPa, which is of little consequence when the object is to measure IMEP. If the purpose is to determine absolute pressure during intake and exhaust however, such an error may well be unacceptable and that in this case a strain-gage transducer, which is an absolute-pressure sensor may be needed or preferable.

Rasswieler and Withrow [33] carried out pioneering studies to correlate flame development with burn rate calculations derived from pressure measurements. During their work, they stated that for simple calculations an average polytropic of 1.3 can be used - it was found that small variation (+/- 0.05) had little effect. It was also noted that in their work, Polytropic exponents for compression and expansion were assumed to be the same but this is not true in reality due to gas composition.

Randolph [29] mentions that in most internal combustion engines, compression is polytropic - but this is not true in cases where mass is lost during compression (blowby, leaking valves), or where excessive heat loss occurs (some diesel engines).

Brunt [34] explored heat release calculation errors specifically in direct injection diesel engine. He proposed an alternative heat release model that was shown to give very good results over a wide range of operating conditions. This heat release model employed a variable polytropic index to cater for the heat transfer, it was found to be very well suited for diesel engine performance and development applications where consistent diesel engine heat release data is required.

Gatowski et al. [35] suggested from their studies into heat release calculations that the most important thermodynamic property used in calculating heat release rates for engines is the ratio of specific heats – gamma

2.2.2 Errors relating to the transducer

With respect to the pressure transducer, Pischinger et al. [36] states there are many potential factors that can affect accuracy. Short term drift (inter-cycle) can be particularly problematic, and difficult to identify when it occurs, also the subsequent affect that it has on the data quality is an issue as it generally cannot be eliminated or compensated for. They propose that a useful technique that can be employed is to undertake a comparison of measured data with simulation data (if this is available). For the pressure measurement, an accuracy on the pressure scale of 1/10 bar in 200 for high pressure measurements, and 1/100 for low pressure measurements is necessary, but in reality, most measurement data has significantly greater errors.

Pischinger et al. [36] mentioned that the largest transducer errors with respect to linearity are generally produced by the transducer itself; the factors involved can include electrical interference, vibration, deformation, temperature and thermal shock. Instability of the transducer is also encountered when the transducer is new, or when it is exposed to extreme operating conditions. In general, Pischinger et al. [36] suggests that non-linearity and instability can both contribute to errors in the region of 1% of full scale.

Davis and Patterson [19] suggest that close monitoring of the average pressure during exhaust stroke (-60 to +60 degrees CA BDC) is a worthwhile observation, as large variation of this will value will occur when thermal shock is present. They also suggest that LogPV (Logarithmic pressure versus volume) envelopes are useful as increase spread occurs during thermal shocking, and this can be seen around gas exchange cycle. These metrics are specifically useful to identify thermal shock, but can also be used to identify other common sources of error.

Soltis [37] evaluated different pressure transducers in one cylinder to examine the combustion measurement differences between them simultaneously. He focused his experiment at full load and low speed operating points. He proposed 4 main metrics for judging sensor accuracy:

- Comparison of averaged data to that gathered from reference sensor of higher accuracy
- Comparison of averaged measurement (500 cycles) in the region of exhaust valve open to an absolute sensor, using an averaged numerical value know as average exhaust absolute pressure (AEAP)

- Comparing the stability of the sensor to itself at specific points in the engine cycle, then showing the relationship of those points during particular sections of the cycle
- Compare the relationship of IMEP to the location for 50% mass fraction burned

Soltis [37] noted that excessive temperature at low speed can cause thermal shock, and that excessive temperature at high speed affects the sensitivity of the sensor. In general, he found that smaller transducers with a face seal can transfer heat away from the diaphragm - but this does not eliminate inaccuracy with this style of sensor and that smaller sensors in general have the lowest accuracy. With physically larger sensors, the main errors are due to the sensor itself, but this can be improved with a heat shield. Heat shields provide thermal protection and do not interfere with knock recognition. Water cooled, flush mounted sensors performed the best overall, but mounting them could affect combustion chamber dynamics.

Schaefer et al. [38] and Stein et al. [39] discuss the effects of thermal stress and strain on the transducers in their work, also, the effects that this can have on data quality. They both discuss the impact of the cyclic, high temperature and heat flow on the transducer accuracy, and the impact on subsequent results, in particular IMEP. It is suggested that transducer sensitivity changes due to temperature up to 100% are possible due to the heat flow in the working environment of the transducer. This would drive a requirement to calibrate the pressure transducers regarding the real temperatures given by engine operating conditions – however, in practice this is rarely done!

Stein [39] suggests that thermal strain does not significantly affect the measured pressure during the gas exchange portion of the engine cycle under motoring conditions, at the compression ratios used in spark ignition engines. Therefore, overlay of the firing and motoring intake stroke pressure data can be used as a method of detecting thermal strain at low engine speed.

Mueller et al. [40] Compared transducers in the same engine cylinder - six types compared to a reference transducer at 2 speeds, 2 loads, 3 ignition timings, constant AFR. The results based on a 200 cycle sample suggest that at the time of the experiment, only water cooled transducers were suitable for thermodynamic analysis. This is no longer true due to piezo-electric technological developments but the work does highlight the problems associated with selecting the correct pressure transducer. Also that the transducer is the most severely stressed part of the measurement chain.

Wenger [41] studied in detail the characteristic of sensor stability and the various types associated in this context. He stated that mounting the sensor produces stresses that can lead to errors of several percent. Overloading and cyclic operation can cause a permanent deformation in material structure that causes an offset of 0.5%. Temperature/long term errors can be larger than that quoted in overall accuracy figures and that ageing can be accelerated with the temperature cycling encountered. Zero point stability is a useful metric - but data is scarce and is not generally available from the manufacturers. Temperature stability – this can be compensated electronically and reduced to a few percent in over 100 degrees span. Changes in element sensitivity and thermal effects on construction material must also be considered. Thermal/Mechanical shock caused by strong temperature gradients cause significant errors – the diaphragm is the most sensitive part that is directly exposed to heat flux - smaller sensor elements have less influence.

Wenger [41] also considered chemical effects - Metallic, spring diaphragms can change elasticity over time due, as a function of exposure to working fluids. Sensor data sheets always state accuracy with respect to a dry, reference pressure in a non-aggressive atmosphere. It is rarely the case the transducer diaphragm is exposed to such a condition. However, Wenger does not quantify the effect on the measurement accuracy itself in his work – only the corrosion resistance of the diaphragm material is mentioned.

Higuma et al. [42] suggest that one of the main measurement errors of piezoelectric pressure transducers, is the error caused by the loss of charge resulting from the characteristics of transfer function of the electric circuit inside the charge amplifier. They proposed a method utilizing error-compensating equations derived from theoretical analysis, using the actual pressure data obtained by piezoelectric transducers. Determination of time constant error was executed via an intermittent heat loading rig, and then numerical compensation methods developed. This was useful work but only considered this factor in isolation, hence interacting effects were not observed. Also, surface temperature measurements were not taken but the estimation method was described in detail.

Puzinauskas et al. [43] made a study to objectively characterise the phenomena of thermal-shock errors on a specific Kistler pressure transducer. The goal being to determine if a thermal-shock correction algorithm, using transducer surface temperature, could be developed. Employing an intermittent heat loading rig, they isolated the effects of thermal shock, and then modelled this phenomenon as a function of surface temperature. Once the model was trained, it was possible to remove 95% of thermal shock error in the specific instance. Puzinauskas et al. [43] stated that thermal shock destroys accuracy of measurement of pumping loss at med-high load. It can have a major impact, for applications involving friction studies. Also stated was the fact that manufacturers spend most efforts to reduce thermal shock via the transducer design. This work could be extended to include mechanical and thermal effects in the model, as the interactions of the effects contributing to overall transducer error are not proven in this work so far.

Davis and Paterson [44] took another approach to reducing the impact of thermal-shock on measurement data quality. In their study, they focussed on mounting techniques that will improve data quality. It was suggested that the average temperature of a thermally protected cylinder pressure transducer will vary from ~100°C at light load to ~200°C at WOT (Wide Open Throttle) for an engine with 90°C coolant temperature, and may exceed 500°C for non-protected flush mounted transducers. Transducer temperature as a function of load and location is shown in Figure 2.4 below.

For this purpose, they developed a new parameter called “Radius Fraction Burned” (RFB), it is introduced to estimate the position of the propagating frame front and when it reaches the transducer face (or connecting passage entrance where applicable). The concept of radius fraction burned, as a technique for the topological accounting of the propagating flame front, and its interaction with the connecting passage and transducer cavity volume, is proposed as an aid for designing the transducer installation. As a general guide, using this RFB metric, it was suggested that the optimal, highly desirable situation is to have the flame arrival at the transducer passage occur after peak pressure. However, it should be noted that generally, by the time the flame front reaches the farthest point of the cylinder wall – typically, only one third (approximately) of the mass has burned. Therefore, large pockets of unburned mass can still exist behind the flame front. Therefore this metric cannot be used in isolation for assessing the quality of the transducer installation.

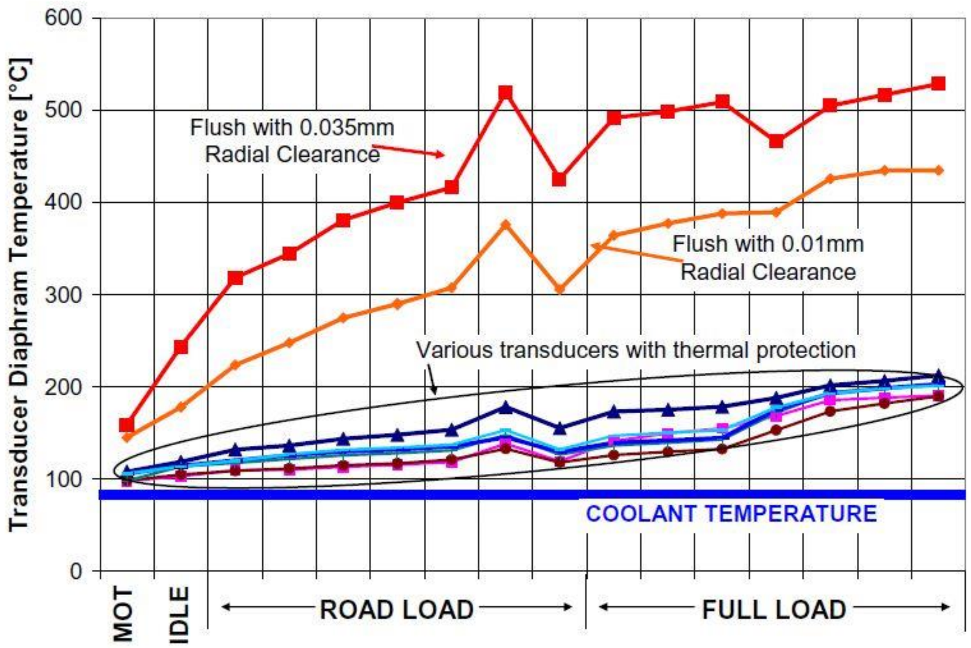


Figure 2.4: Transducer operating temperature as a function of operating condition and mounting scheme [44]

Rai et al. [45] studied in detail the effect of thermal shock, and its impact on IMEP. They noted that thermal shock is a major problem and IMEP accuracy can be affected by up to 10% of the measurement range. Rai et al. [45] noted that the most significant impact was at low speed and high load (where heat flux to the transducer would be at its greatest). In addition rich mixtures and low EGR rates also tended to increase the errors. In summary, they concluded that in their experiments, thermal shock was generally a function of burn time and peak pressure – but this needed more experimental work to increase confidence in this statement. Numerical methods based on peak pressure and engine speed were developed compensate the thermal shock effects, and these proved effective in this specific case, but it was not proposed in the work that these would be generally applicable without further investigation. Figures 2.5, 2.6, 2.7 and 2.8 below all show the effect of some of the various errors explored in the literature, in comparison

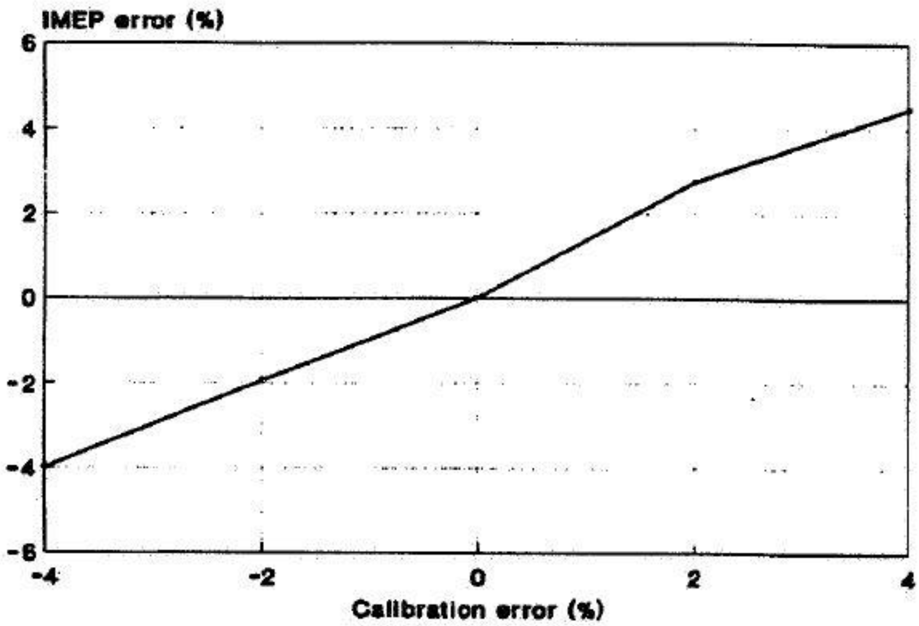


Figure 2.5: IMEP error versus transducer calibration error [48]

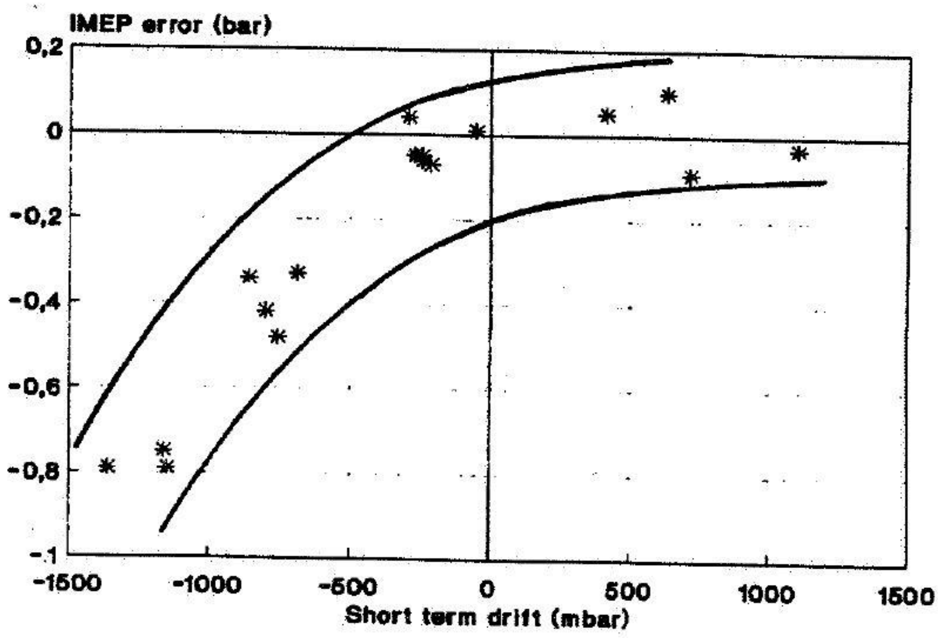


Figure 2.6: IMEP error versus transducer short term drift [48]

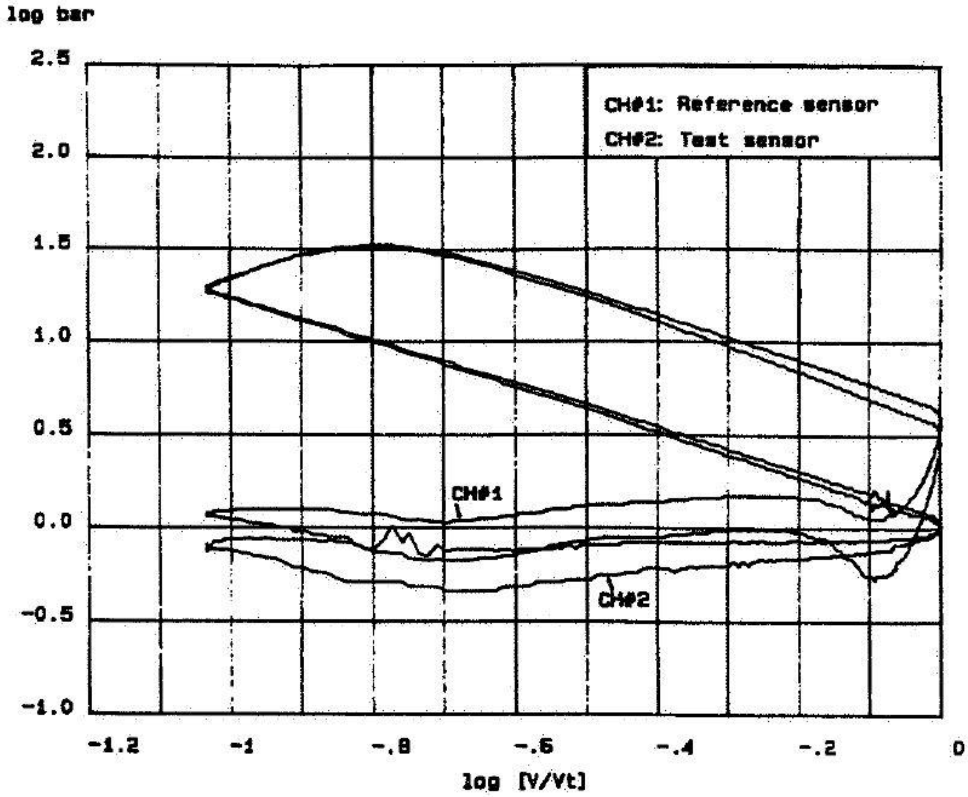


Figure 2.7: Log PV diagram – effect of short term drift comparing to a reference sensor [48]

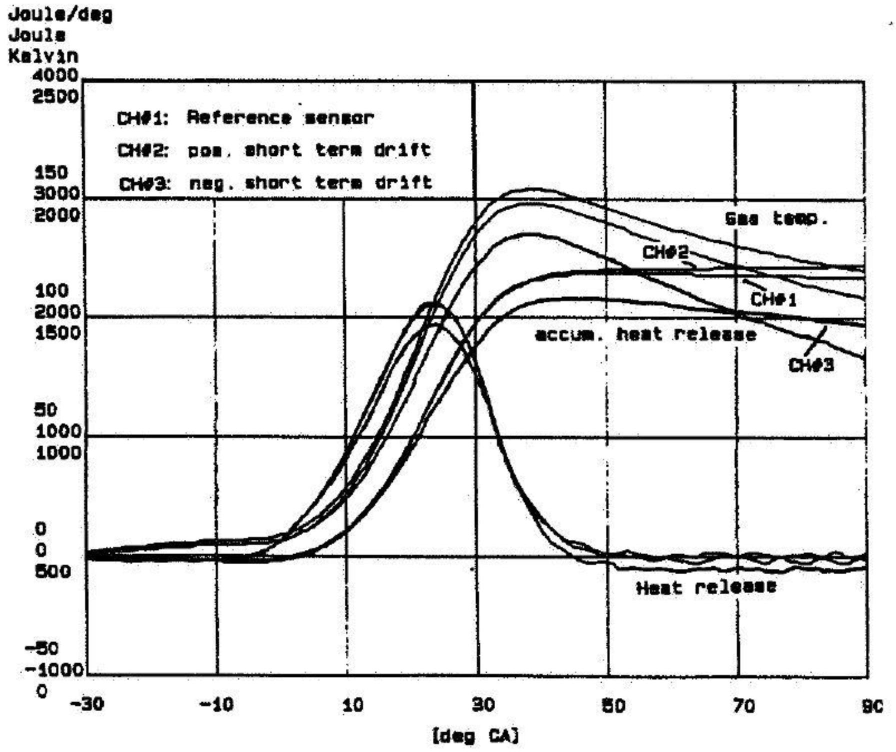


Figure 2.8: Effect of short term drift on heat release calculations, comparison to reference sensor [48]

2.2.3 Errors relating to the encoder system

The angle encoder is a critical part of the measurement system and provides a reference for the pressure data as it is recorded through the engine cycle, it is imperative therefore that the measurement of this is at a level of accuracy suitable for the task at hand. For example, uncertainties of the order 0.1 degree crank angle can result in errors of around 1 bar in calculated friction mean effective pressure (FMEP). As a consequence selection and installation of an encoder of appropriate resolution is essential.

Kuratle et al. [22] suggests that the encoder system must be rugged, with external electrical grounding and possess the capability for high resolution (for steep combustion peaks). In general, it is stated that 1 degree crank angle resolution is sufficient for accurate IMEP calculations in gasoline engines (no steep pressure gradients). TDC must be determined within 0.1 degree CA (Crank Angle) hence the encoder system must be capable of producing marks with this resolution.

Brunt et al. [46] made a detailed study into the effect of crank angle measurement resolution on cylinder pressure data. Brunt [46] used simulated and experimental engine cylinder pressure data and suggested that CA resolution is one of the most important variables to be considered when measuring and analysing engine cylinder pressure data. In this work [46], a major factor suggested as a source of error was the interaction between ADC (Analogue to Digital Converter) resolution and crank degree measurement resolution.

Brunt [46] suggested that when combined with high CA resolution, the ADC resolution error can produce very large noise spikes in those derived parameters which are functions of the cylinder pressure change rate.

A solution proposed is to use a variable crank angle resolution during the measurement, ideally, to be able to vary this as a function of pressure change. This technique was shown to be very effective for reducing noise without loss of bandwidth during parts of the cycle where high rates of change occur.

In summary, Brunt [46] suggested that for SI engines, a high CA resolution should only be required for knock analyses. Assuming that the main pressure oscillation frequency during knock is circa 5 - 10 kHz, a CA resolution of at least 0.2 degrees would ideally be used at low engine speed (this would give a sampling frequency of 30 kHz at 1000 rpm for example). For the remainder of SI (Spark Ignition) engine work where parameters such as pressure rise rate, mass fraction burnt (MFB), IMEP etc. are required, a CA interval of 2 degrees would perhaps be optimum since compared to 1 degree CA resolution, twice as many cycles could then be acquired and processed for the same level of resources. For CI (Compression Ignition) engine heat release analysis, Brunt [46] suggests a CA resolution of between 0.5 degrees and 1.0 should be most appropriate.

For IMEP determination, Brunt [46] states that relatively coarse CA degree resolution could be used without incurring significant errors. For real time applications, CA resolution of up to 10 degrees should be possible, especially if suitable low pass filtering (i.e. negligible attenuation and phase shift at low) is employed. Brunt et al. [47] also mention in this context that the effects of coarse crank angle resolution, incorrectly specified connecting rod length, signal noise and integration period error should be relatively small with respect to IMEP. It was noted in this work [47] again that IMEP is very insensitive to the crank angle resolution used for the calculations and that resolutions much greater than the 1.0 degree commonly used could be adopted without serious loss of accuracy. In Figure 2.9, the sensitivity of IMEP to measurement resolution is shown for sensors with low and high drift sensitivity.

It should be stated here that most commercial combustion analyser do allow variable data acquisition rates within an engine cycle. State-of-the art systems generally can support 3 levels of measurement resolution, although for most purposes, 2 is sufficient.

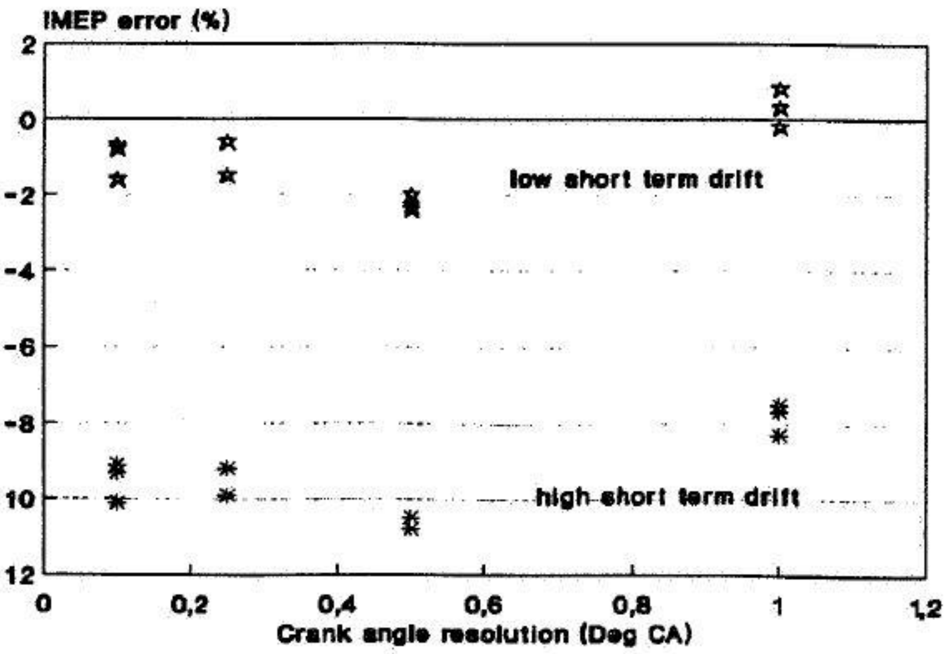


Figure 2.9: IMEP error as a function of measurement resolution – sensors with low and high short term drift properties compared [48]

2.2.4 Errors relating to measurement chain hardware

In a typical combustion measuring system, the engine mounted measurement parts have to be connected to the data acquisition system. The components used for this can also be sources of error and are mentioned in appropriate literature.

Brunt et al. [20] stated that signal noise should not produce significant errors for normally defined burn angles but can cause problems with burn angles below 10% and above 90% and major problems with burn rates. Kuratle et al. [22] mentioned that optimum selection and maintenance of the system, keeps errors to a minimum, but the Engineer must also be able to interpret results that may not be 100% correct. In general he stated that the overall system accuracy depends on the accuracy of each component, in combination with correct signal analysis.

Kuratle et al. [22] made a detailed study of the influencing factors and error sources in a combustion measurement. He noted that mechanical noise can be an issue and the sensor mounting location is a critical factor – Low pass filtering can be used but phase shift can affect the accuracy of IMEP (as shown in Figure 2.10). Cable/Electrical noise can be significant and insulation breakdown causes drift – Kuratle [22] stated that the delicate part is interface between a sensor and amplifier - dirty connectors - also cable movement – cause problems and for this reason it is better to place the charge amplifier in cell. Electrical noise from ignition systems can be avoided using shielding, and also via careful placement of cables away from noise sources.

Ground loops due to different ground potentials between sensor and amplifier – and amplifier and measurement system – are the source of signal interference and noise in many cases as it tends to cause a ripple on the display (mains frequency). But, this can be reduced with a thick external ground cable between the engine and charge amplifier ground. Also, this factor can be avoided with ground isolated sensors!

Randolph [31] studied error effects in the whole measurement chain, particularly with respect to testing High-Performance (HP) engines which is the most challenging environment for a combustion pressure measurement. He stated that overall, care must be taken when instrumenting the engine, acquiring data, and interpreting results – and this can be considered a general statement for all applications of combustion measurement. Mechanical noise from valve closure noise can be a problem in HP engines – Randolph [31] suggests that mounting the sensor in the block (head gasket acts a vibration damper) is a possible workaround (however, this is rarely done in practice!). Drift effects - aggravated by high temperatures – can be managed by maintaining the amplifier gain, at a low level with a longer time constant. Randolph [31] concurs with Kuratle [22] that all connections must be clean. Also that the user must set the system to make best use of digitiser range wherever possible! As a final statement to his work, Randolph [31] mentioned that detailed Heat Release analysis is not appropriate with any known inaccuracies in the data!

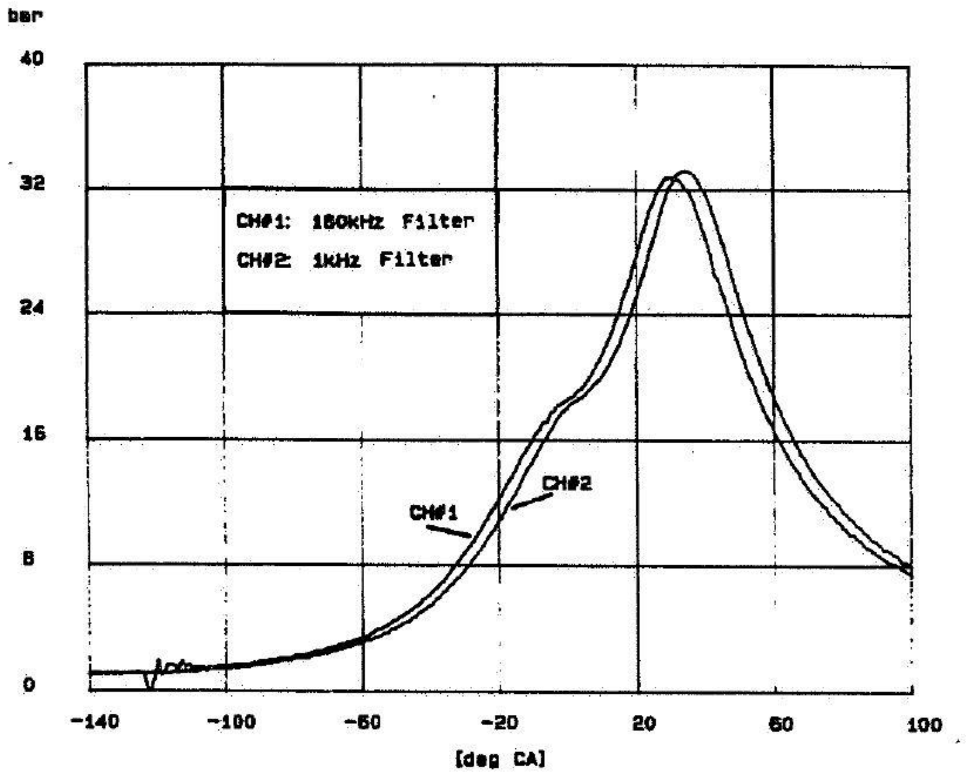


Figure 2.10: The effect of filtering on TDC position [48]

2.3 Summary

During the process of researching the literature for this work - many interesting developments were noted in specific areas of combustion measurement technology and application. As previously mentioned, the information that can be derived from a cylinder pressure curve is decisive during the development phase, and the application field is broadening continuously over time - driven by powertrain legislation (for example in-vehicle measurement to support development and calibration of powertrain control units and systems). However, there have been many interesting attempts to derive combustion related data, with a simpler or easier to implement approach, for other purposes. Namely, to be able to apply combustion measurement, in series production applications, as opposed to being a research tool - the drive being to achieve improved levels of system control, or for condition monitoring purposes. This has led to numerous interesting approaches to sensor and measurement technology, also, to interesting concepts for some model based approaches for gaining the required information.

In the literature, many authors are focussing particularly on transducer related errors (as these are a significant contributor). Kuratle [48] states that every sensor selected is a compromise of factors but in general - Miniature sensors are ideal for multi-cylinder applications – but water cooled sensors are ideal for highest accuracy. At the time of writing though, there seemed to be no suggested combination of methods, approaches or metrics that suggest overall data quality, either prior to measurement start (qualifying the system set-up quality and readiness) or for use online, during a measurement procedure (to warn of potential issues that could affect the data quality during runtime, so that evasive action can be taken of required).

Cyclic variation should also always be considered when averaging or reducing data – this involves reducing a number of measured engine cycles (taken at a particular engine operating condition) to a single, representative engine cycle. This is an often used technique, with limited understanding of the overall accuracy of the output and its relevance to the task.

Spark ignition engines tend to suffer more with cyclic variations as successive engine cycles are never the same - due to the continuously changing in cylinder conditions with respect to temperature, pressure and flow. Compression ignition engines are less susceptible to cyclic variation due to the fact the in-cylinder charge is not pre-mixed. In general, in order to achieve a reasonably representative single, mean cycle for an engine condition, a minimum of 300 cycles is suggested for spark ignition, with 200 being the minimum for other combustion system/fuel types (Compression/HCCI/PCCI).

3 Combustion pressure background

This chapter provides specific information regarding the errors sources that are the focus of this investigation. In particular, with respect to their impact on overall data quality. As supporting information, commonly used CPM calculations are reviewed as pre-requisite information, prior to discussing the development process and requirements of the data quality metrics.

3.1 Dynamic and static sources of error

For the purpose of this study, the main areas of concern with respect to CPM data quality influencers are proposed. Namely - Correct TDC allocation, correct pressure referencing (Pegging), correct definition of critical thermodynamic and engine parameters. Most of these settings are defined during the initial set-up of the system. In the author's experience, this is the area which is the root cause of many data quality issues. Figure 3.1 below shows a log pressure versus the volume plot, with the effect of these and other typical errors (discussed in literature) highlighted.

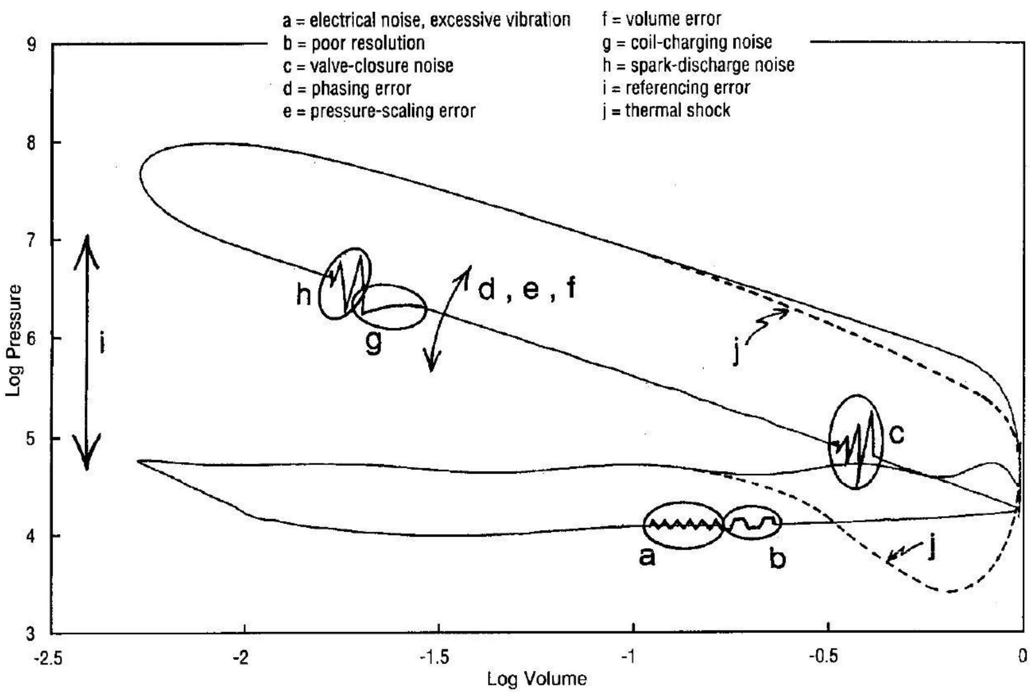


Figure 3.1: Examples of the effect of several types of errors and how they can be identified from the Log Pressure-Volume diagram [31]

It is possible to group these errors into 2 main sub-domains as follows:

3.1.1 Static parameterisation errors

These are errors that can be considered as simple parameters that have to enter during the system set-up. It is often the case that sometimes certain values will simply not be known, or will be estimated. This can be acceptable for relative type measurements or comparisons. However, consistency is not a measure of accuracy. In some cases, values need to be accurately established or known. For example, engine geometry is needed to establish instantaneous cylinder volume. These geometric parameters are normally known – but a special case to consider is the compression ratio. This value is difficult to measure accurately and thus cannot be easily confirmed. In addition, the compression ratio can vary during a measurement due to dynamic operating conditions – hence, this is a parameter value than can be considered ‘high risk’ with respect to data quality. The effect of incorrect compression ratio is shown in Figure 3.2 below.

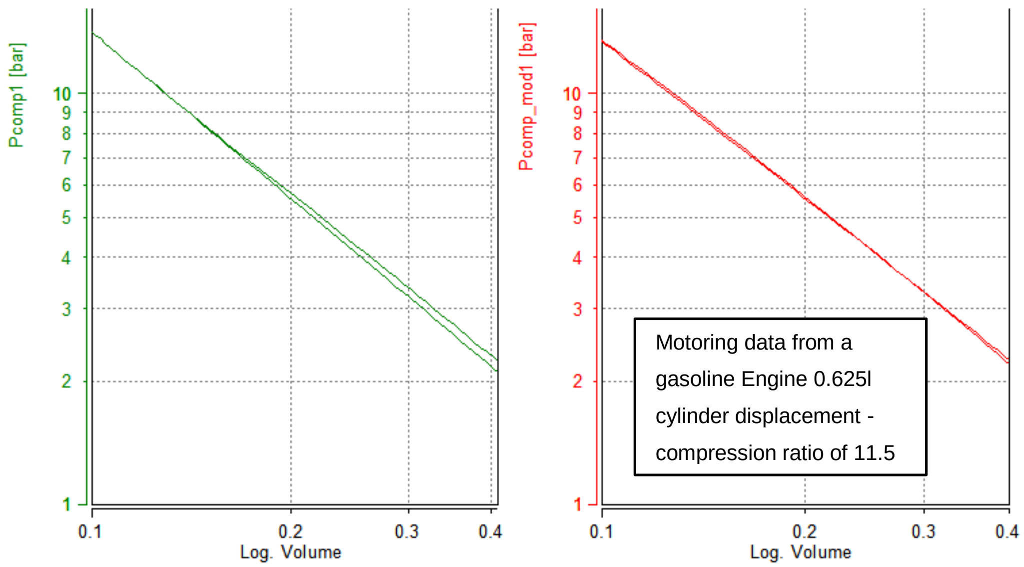


Figure 3.2: Effect of incorrect compression ratio definition, of -1 ROC, on the motored Log PV diagram (RHS)

Another example would be the polytropic coefficient which defines the process of expansion and compression – and is used in several indirect calculations. This value is often assumed as constant throughout the process, in reality this is never true and thus, this value can be a source of error with respect to these further calculations. However, to really establish the polytropic coefficient with accuracy, during run-time, is nearly impossible due to the inhomogeneous nature of the working fluid and the dynamics of the combustion process – therefore an estimated value is always employed which needs expert knowledge in order to be able to define the correct value for a given application or measurement. The effect of incorrect polytropic on the calculated heat release curves definition is shown below in Figure 3.3.

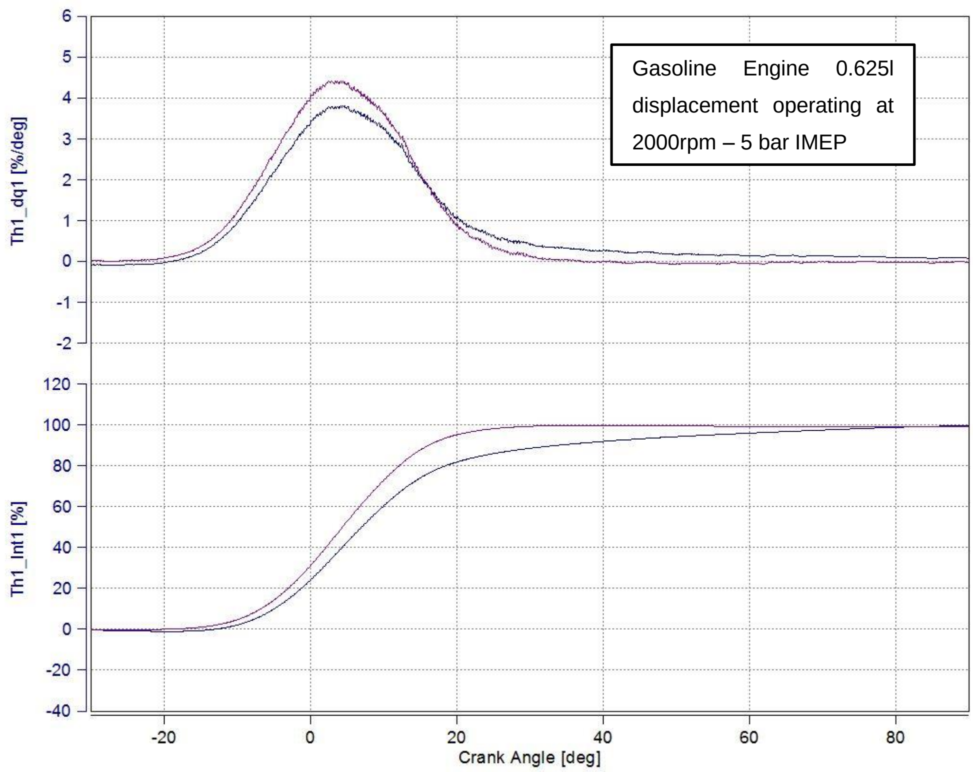


Figure 3.3: Effect of +0.1 incorrect polytropic definition on heat release calculations (blue lines are correctly measured curves)

3.1.2 Dynamic run-time errors and effects

Dynamic errors are those which have most impact during operation (i.e. measurement runtime). In general, the most important factor for a combustion measurement is to correctly assign phasing of the diagram with respect to crank angle, and pegging of the measured curve on the pressure scale (cycle-by-cycle). If these two factors are correct, then the raw data will be of acceptable quality, at least for the post-processing phase. If either of these is compromised, then the data is effectively void – this could mean a considerable waste of time or effort.

Correct phasing (also known as TDC determination) is normally established in a pre-procedure, prior to actual measurement. There are various methods in common use and assuming this procedure is executed correctly, acceptable levels of accuracy can be achieved. However, during run-time, there are factors (mechanical and electrical) that can affect the encoder – electrical noise, resonance effects – in addition; there are factors that can be related to the engine itself (mechanical loading). These can actually change the phasing subtly, depending on operating conditions, and the specific engine cylinder. This can produce errors in the data that are very difficult to identify during run time, and may only become apparent in the data much later in the evaluation process. The effect of TDC error on Log Pressure vs. Volume plots can be seen in Figure 3.4

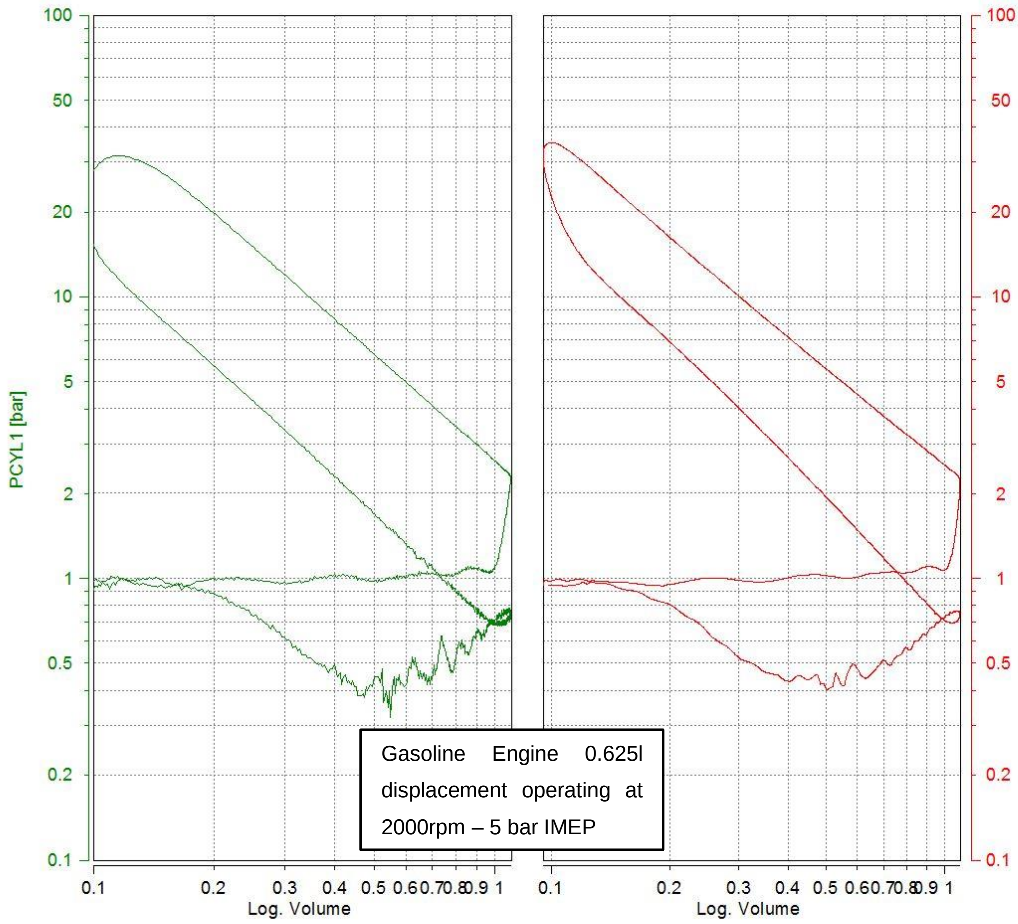


Figure 3.4: The effect of a + 2 degrees CA TDC error on the LogPV plot (RHS)

Pegging or offset correction can also be considered as a 'dynamic' error. The effect of this error on heat release curves is shown in Figure 3.5. There are several methods available to correct the pressure curve, on a cycle-by-cycle basis, with respect to being able to establish the absolute pressure value at the sensor measuring face. This basic requirement is needed due to the fact the piezo-electric sensors are only able to measure dynamic pressure change, not absolute pressure (due to the measuring principle involved), thus some correction method is needed. Errors can occur depending on the method chosen (i.e. appropriate for the application), also, the operating condition of the engine. In addition, other factors, for example correct phasing, can have an impact depending on the method. The correct value has an influence on evaluations made directly on the curve, also indirectly, the latter being greater risk of error, by approximately an order of magnitude.

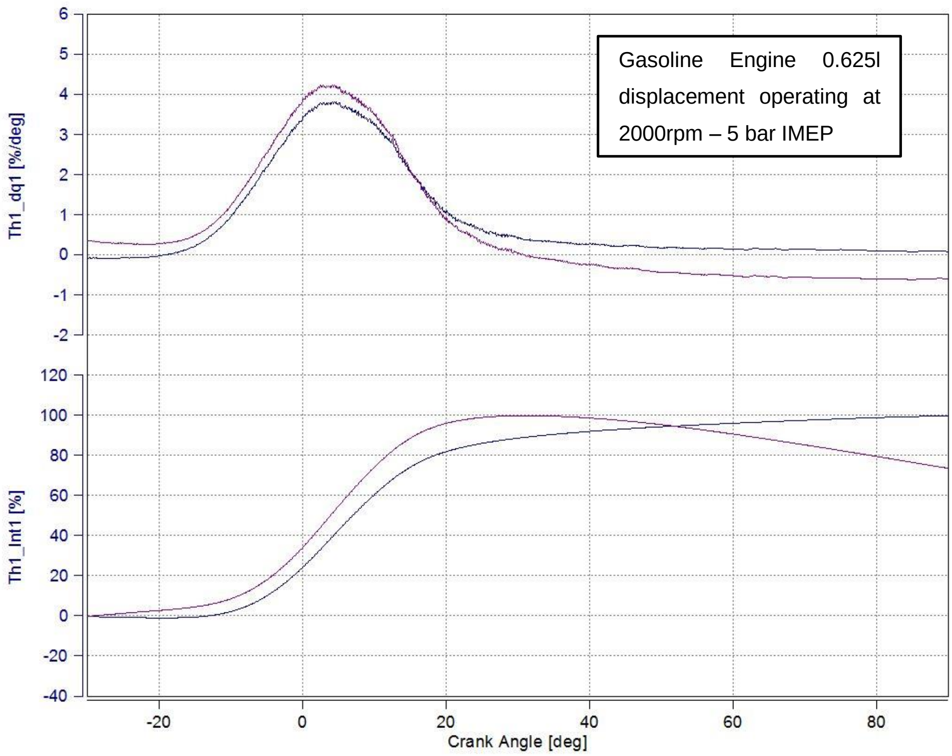


Figure 3.5: Effect of incorrect pegging (zero level correction) of -2 bar, on heat release calculated curves (blue curves are correctly measured data)

3.2 Common calculations and results

3.2.1 Indicating measurement equations

From the acquired data (nominally pressure and volume/crank angle) a significant number of derived calculations are typically undertaken to establish performance of the engine combustion system and the combustion process.

It is therefore a useful to review the calculations involved, in order to be able to appreciate the need for metrics that can give an overall rating of data quality such that the user can be confident in calculations.

3.2.2 Cylinder volume

Prior to operation several engine specific variables need to be known and used in order to calculate cylinder volume, these are:

- Cylinder bore (*B*)
- Crank radius (*a*),
- Connecting rod length (*l*)
- Compression ratio (r_c).

To avoid unnecessary repetition of calculations, cylinder volume (*V*) is calculated using Equations 3.1 through 3.4 for each crank angle division as required according to the measurement table and resolution.

$$V = V_c + \pi\left(\frac{B}{2}\right)^2 (l + a - s) \qquad [3.1]$$

Where s is the distance between the crank axis and the piston pin axis and calculated by

$$s = a\cos\theta + \sqrt{\left(l^2 - a^2\sin^2\theta\right)} \qquad [3.2]$$

Swept volume (V_s) and clearance volume (V_c) are calculated thus:

$$V_s = 2a\pi\frac{B^2}{4} \qquad [3.3]$$

$$V_c = \frac{V_s}{r_c - 1} \tag{3.4}$$

A shaft encoder mechanism will supply both crank angle and trigger marks to the measurement system. The crank degree marks initiate Analogue-Digital samples and hence set the acquisition frequency which is engine speed dependant.

The accuracy of the volume calculation is limited by the accuracy to which the clearance volume can be measured or determined. In addition, the accuracy of the crank shaft displacement measurement (via the angle encoder) also has a significant effect on the accuracy of instantaneous cylinder volume determination. Note that clearance volume is not required for MEP related calculations, as it is only the change in volume relative to pressure that is considered here.

3.2.3 Pressure correction (or pegging)

The process of pressure correction is known as pegging and consists of calculating and correcting for the measured signal voltage applied to the measurement system input channel at a crank angle where absolute in-cylinder pressure is known. There are several pegging methods available, the simplest and most common is to set in-cylinder pressure at Inlet BDC (IBDC) equal to inlet manifold pressure. This method is known to work well for un-tuned normally aspirated engines, though is unsuitable for engines with highly tuned intake systems or those with forced induction, where more exotic means are necessary. Another approach is to measure a correction pressure value, in the manifold, or at BDC via access in the cylinder wall, by a second, piezo-resistive (absolute), pressure transducer.

Where an absolute reference pressure is not available automated pegging calculation based upon the polytropic equation $(pV^n = \text{constant})$ can be used, described below.

The change in pressure experienced during the compression stroke due to the volume changing from V_1 to V_2 can be written as shown in Equation 3.5:

$$\Delta p = p_1\left[\left(\frac{V_1}{V_2}\right)^n - 1\right] \qquad [3.5]$$

Where p_1 and V_1 are the cylinder pressure and volume at crank angle$_1$ and likewise for p_2, V_2 at crank angle$_2$.

3.2.4 Indicated mean effective pressure

The indicated mean effective pressure (IMEP), can be calculated as the integral of the pressure volume curve divided by the swept volume (Equation 3.6). IMEP can be presented in either gross or net form, the former accounting only for the work done on, or by, the piston during the compression and expansion strokes, the latter also including the work done by the piston in the exhaust and inlet strokes.

$$imep = \frac{1}{V_s}\oint pdV \qquad [3.6]$$

Graphically, this can be explained by Equation 3.7

$$\mathrm{imep(gross)} = \frac{(\text{area of power loop})}{V_s} \qquad [3.7]$$

Or net IMEP, as calculated by the heat-release system in Equation 3.8

$$imep(net) = \frac{(\textit{area of power loop}) - (\textit{area of pumping loop})}{V_s} \qquad [3.8]$$

If several cycles are analysed, the coefficient of variation (COV) of IMEP can be determined as shown in Equation 3.9

$$COV = \frac{\sqrt{\sum_{1}^{n}\left(imep - \overline{imep}\right)^2 / (n-1)}}{\overline{imep}} \qquad [3.9]$$

Since IMEP is a direct measure of combustion performance, it follows that variations in its value are a direct indication of combustion stability. It is highly sensitive to correct phasing of the pressure data (TDC determination), as well as being compromised by transducer thermal shock and sensitivity errors.

3.2.5 Instantaneous energy release (heat and burn rate)

One of the most important calculations for the Engine Engineer is the ability to gain a mass-burnt fraction (MBF) profile curve in real-time. Having the knowledge of the rate at which fuel is burnt can aid understanding of the entire combustion process. Several methods, of varying complexity, exist for this type of calculation, though a simplistic one-zone heat-release approach is generally deemed to be sufficient for qualitative analysis and computationally efficient. By treating the combustion chamber as a single zone system in which some of the combustion charge/products escape an energy analysis can be undertaken. This analysis result in Equation 3.10 below that shows the amount of chemical energy released as combustion proceeds.

$$\delta Q = dU + \delta Q_w + \delta W + \Sigma hdm \qquad [3.10]$$

Where δQ is the chemical energy released, dU the change in internal energy of the gas mixture, δQ_w heat transferred through the cylinder walls, δW the amount of work done by the gas (equal to $pdV$and Σhdm the energy lost due to any blow-by.

Making use of the ideal gas law and neglecting any gas leakage, crevice volumes and heat transferred from the cylinder means that knowing cylinder pressure, p, the amount of energy released as combustion proceeds can be calculated using Equation 3.11;

$$\delta Q = \left(\frac{C_v}{R}\right) Vdp + \left(\frac{C_v}{R} + 1\right) pdV \qquad [3.11]$$

Where Cv is the specific heat capacity and R the gas constant.

Knowing the heat release rate, it is possible to determine the progression of combustion i.e. start and finish as well as other important events such as the point at which 50% of the charge has combusted, etc.

The integral heat release may also be determined by integrating the Expression 3.11. From this, efficiency can be evaluated since its maximum value [J] is the total energy released as shown in Equation 3.12. Where the integral is evaluated from the start, a to the end, b of combustion. The mass of fuel, m_f multiplied by its lower heating value, I_f less the sum of internal energy, U_f of the exhaust gas components and the chemical energy available in the products, $m_u I_u$.

$$\eta = \frac{\int_a^b \frac{\delta Q}{d\theta}}{m_f I_f - (U_f + m_u I_u)} \qquad [3.12]$$

Other important observations that can be made from the heat release rate and integral heat release are;

- Ignition delay time – time between the spark event and the start of combustion.
- The time at which the mass fraction burned is equal to 50%.

Note that most heat release calculations are relatively simple and have significant assumptions made in order to minimise processing time so that they can be executed quickly. The most notable are:

- No blow-by loss past piston rings
- No wall heat transfer – pure adiabatic process
- A constant polytropic coefficient throughout the cycle

3.2.6 Polytropics

In a purely polytropic process, the relationship shown in equation 3.13 will be obeyed throughout:

$$PV^n = C \qquad [3.13]$$

Where P is the pressure, V is specific volume, n is the polytropic index and C is a constant.

The polytropic process equation is particularly useful for characterising expansion and compression processes which include heat transfer. We can use this calculation to create a crank angle based curve of C (where n can be estimated). This curve shows a strong response during the compression/expansion process where combustion takes place and can be used to identify start and end points.

The polytropic coefficient itself can be determined between two data points on the pressure curve. It is of particular interest during compression and expansion processes and can be derived as a single result between two points, or as a continuous curve versus crank angle. The calculation is shown below in equation 3.14

$$X = \frac{\ln P_1 - \ln P_2}{\ln V_1 - \ln V_2} \qquad [3.14]$$

Where X = Polytropic coefficient, P = cylinder pressure at crank angle location 1 or 2, V = cylinder volume at 1 and 2 respectively

Most practical thermodynamic process can be considered polytropic with values ranging between the theoretical limits of 1 to 1.4. The value can also be considered as defining the gradient of the compression and expansion lines on a logarithmic pressure/volume diagram.

3.3 Summary

When data has already been acquired it can analysed with a focus on several areas of particular importance with respect to the overall task. At this point problems can commonly become apparent:

- Correct pressure-volume relationship with respect to crank angle
- Correct definition of parameters for calculation of cylinder volume
- Correct positioning of the pressure curve relative to atmosphere

- Correct scaling factors/transfer functions used in the signal conditioning
- Correct definition of coefficient for defining extrapolated process curves

The main components in the measurement chain are classified in the table 3.1 below with respect to the instrumentation error effect:

Table 3.1

	Transducer and cabling	Amplifier	Encoder	Measurement Device
Drift	Significant	Significant	Non	Non
Linearity	Significant	Some	Non	Some
Stability	Significant	Significant	Some	Some

Table 3.2 in shows the measurement chain components classified with respect to their sensitivity to external interference:

Table 3.2

	Transducer and cabling	Amplifier	Encoder	Measurement Device
Electrical Noise	Significant	Significant	Significant	Significant
Vibration	Significant	Non	Non	Significant
Temperature	Significant	Some	Some	Some

In summary, combustion pressure measurement best practice has been well documented, but the information available is also fragmented. Kuratle [48] states that over one third of engine tests now include combustion pressure measurements and due to the technology drivers of reducing CO_2 and fuel consumption, this trend is growing and the application areas are expanding. Steiner [49] states that using combustion diagnosis systems in combination with an ECU application system to measure data in correlation to the combustion cycles has opened new insight into the processes and the interrelations between ECU, injection system, combustion system, exhaust system, engine mechanics, on-board electronics and other parts of the vehicle. Steiner [49] suggests the requirement that only synchronised data from all sources allows analysing cause and effect of processes within the complex vehicle drivetrain. This drives a clear requirement that good quality combustion data is now required more widely in the development process, not just at an engine test bed environment. In the context of this study, this means that more Engineers will need good quality combustion data, and there may be more Engineers trying to measure this data who have less experience and ability to judge good quality data – it is for this requirement that objective data quality metrics would be very useful.

4 Algorithm development and implementation

This section defines the basis for the following experimental study. The main error sources with respect to the measurement application are discussed in detail – these will be the main inputs that will be studied as they have the greatest effect in a working environment. In addition, the performance requirements for the developed metrics are stated.

4.1 Definition of the metrics

As outlined in Chapter 2 there are many factors that can affect the overall quality and success of a combustion measurement. Within the scope of this project it has been decided to concentrate on four main error sources. It is estimated by the author that more than 80% of combustion measurement data errors relate to these;

1. Errors relating to incorrect assignment of the position of the calculated volume table with respect to crank degrees - This is more commonly termed as TDC (Top Dead Centre) error as this term implies that the derived TDC and physical TDC are different. This error source can cause significant problems derived results that rely heavily on the correct pressure/volume relationship.

2. Errors relating to correct positioning of the pressure curve on the pressure axis – Relative (not absolute) in cylinder pressure is usually recorded. This is a consequence of the use of piezo-electric sensors. Hence, the pressure signal from the piezo-electric sensor must be set relative to some datum and integrated in order to gain a trace of pressure versus, crank angle or time. The datum may be chosen using one of several available. In addition, amplifier settings must be correctly parameterised in order to achieve the correct transfer function within the amplifier to convert charge to a measurable (voltage) signal.

3. Compression ratio and clearance volume – It is important to correctly define these engine parameters as they are used in the calculation of

the volume table. Cylinder volume can be derived easily by calculation, being mindful of manufacturing tolerances. However, the clearance volume is quite difficult to establish correctly. The actual clearance volume can be determined via the liquid displacement method; this is quite accurate but is very seldom actually carried out. In addition, this method cannot account for dynamic changes in clearance volume that can occur when the engine is running and subjected to normal thermal and pressure induced loads.

4. Definition of Polytropic index – this index defines the thermodynamic processes and is used for deriving and extrapolating several curves of significant interest with respect to combustion pressure measurement. However, the value is not constant throughout the cycle (although it is often assumed to be for the purpose of simplifying calculations). If a single value is used, it can be difficult to propose a suitable value. If a varying value is used, this can be computationally inefficient, and it can also be difficult to decide what value to use in what part of the cycle, as the in-cylinder conditions can vary so significantly, even at the same engine, but at different operating points – the polytropic index is also used in certain methods of pressure referencing correction, so, depending upon application, errors with this factor can have an impact in this area as well!

These are the four factors that will be used in combination in this work - to establish metrics for ‘good’ quality data. They will be proposed as to their suitability as an input to an overall data quality indicator metric that could be developed for use in post-processing or during measurement run-time.

4.2 Sensitivity requirements for the metrics

The metrics must be sufficiently sensitive in order to be able to react within the required boundary such that data errors are detected reliably, without false triggers. For this reason, limits were defined for each variation, within which a suitable response from a given output parameter should be noted, these limits were:

4.2.1 TDC error

The boundary for this this error was within plus/minus 2 degrees crank angle. However, as even small errors in TDC can cause large errors in subsequent volume related calculations, therefore, it was decided that any output response must be able to detect an error with a minimum sensitivity of 0.2 degrees crank angle.

4.2.2 Pressure scale errors

Any output metric must be sufficiently sensitive to detect errors on the pressure scale of a minimum of plus or minus 0.5 bar absolute. Although higher errors could normally be tolerated on this axis, it was decided to limit to 0.5 bar for that sake of indirectly calculated results.

4.2.3 Compression ratio

The static compression ratio can be difficult to measure accurately, as discussed in a previous section, establishing the clearance volume accurately can be a time-consuming and challenging task. In addition, the actual dynamic compression ratio during run time can vary considerably due to engine operating conditions, and engine type. Therefore, a very close tolerance on the compression ratio error could be unrealistic. So it was decided in this case that, if the compression ratio error could be detected as a factor of plus or minus one, as a proportion of the theoretical static value, then this would be sufficient in combination with the other metrics.

4.2.4 Polytropic coefficient

The Polytropic coefficient has a significant effect on heat release calculations, the range between theoretical maximum and minimum values is only 0.4 (i.e from true isothermal to adiabatic processes). Therefore, it was deemed necessary to be able to detect errors within a value of 0.01 absolute if possible. Although this may be difficult to achieve, it may be possible to use the polytropic value in a different analytical approach to detect errors rather than looking a specific tolerance boundaries around the absolute value (for example, comparing the values at different parts of the cycle in terms of a ratio).

During the development of the metrics, these key parameters will be the main focus of the study. The target being to produce metrics with sufficient response to detect errors within the tolerances stated.

4.3 Defining the metrics to be prototyped

From the curves that were developed, calculated results were derived and these were used as a basis for the analysis, in order to examine their response, with respect to stimulation of inputs (or error stimulation). Based on the authors experience, result calculations were developed to cover each of the four main sources of error proposed above. The responses of the various metrics were then used to create models which could be studied for amplitude and interaction characteristics. The key factors considered are stated below:

- It is known that IMEP results have a strong response to TDC errors, therefore results of Gross, Net and pumping IMEP were identified as suitable candidates. These were used in combination and normalised (as percentages) in order to study the responses
- Heat release results are sensitive to the pressure/volume relationship, as well as fixed parameters like the polytropic coefficient. Results derived from the heat release curve were therefore considered to have potential as a quality metric. In particular the gradient of the integral curve at specific crank angles was studied, as well as energy conversion points, late in the cycle. In addition, subtraction of these results were also studied
- The polytropic curve is derived from the pressure/volume ratio; it was considered that this curve may have good response for identifying errors in these areas. Results were derived from the basic curve, as well as a filtered and rectified polytropic curve. Integral values between 2 specific angle positions were considered as well as polytropic values at specific positions on the curve. These results were simple approaches to characterise the raw curve, with singular results that would show a response which could be explored as potential for a quality metric.

- Finally, results from the process constant curve were considered. This curve shows good responses to errors in pressure/volume and process. It can be used to characterise the start and end points of combustion with good accuracy, and therefore was considered to have high potential as a quality metric. The raw curve, as well as the first and second integral was examined and results created to try and characterise the curve with respect to gradient.

The full list of the above mentioned curves, plus the subsequently derived results, for model based analysis are listed in Appendix C. At this point, the main focus of this work was proposed to be able to identify some suitable result based responses that showed potential to be used as data quality metrics. The goal was to find two metrics, with suitable response, for each error case (total of eight). It was suggested that these could be used in combination, to identify a combustion pressure curve data set that has one or more of the proposed errors, from a single cycle of data.

4.4 Software and development environment

To undertake the analysis and ultimately develop the quality metrics the tools chosen were AVL Concerto™ and Cameo™, these are described below. The decision was made to use industrial platforms software for several reasons:

- Using a standard platform means that developments made in the thesis are easily portable into a working environment
- Developing in an industry standard tool (as opposed to a prototyping environment) assists in the validity of the work, and the contributions made
- Porting of development innovations, for use in a standard product as a new feature or USP (Unique Selling Proposition) is easier to implement and could have commercial value

A unique approach in this work was the ‘coupling’ of the tools. Concerto was used for Automation and Simulation, Cameo was used for model building and data analysis (of the models).

4.4.1 AVL Concerto™

AVL Concerto is a data processing tool and platform that can be deployed within a working environment, as a standardised solution for test data processing, analysis and reporting. An overview of the product structure is shown in Figure 4.1. One of the main benefits of the tool is that it can read many types of common data file and database formats encountered in test and development environments. In addition, the software has the capability to align many of the asynchronous data that would be encountered. For efficiency in work processes, the software uses a 'template' concept for generating reports that means data visualisation and processing can be standardised.

In this work, Concerto was used as a simulation environment where calculations could be prototyped, tested and initially assessed – before moving onto the testing and modelling stage.

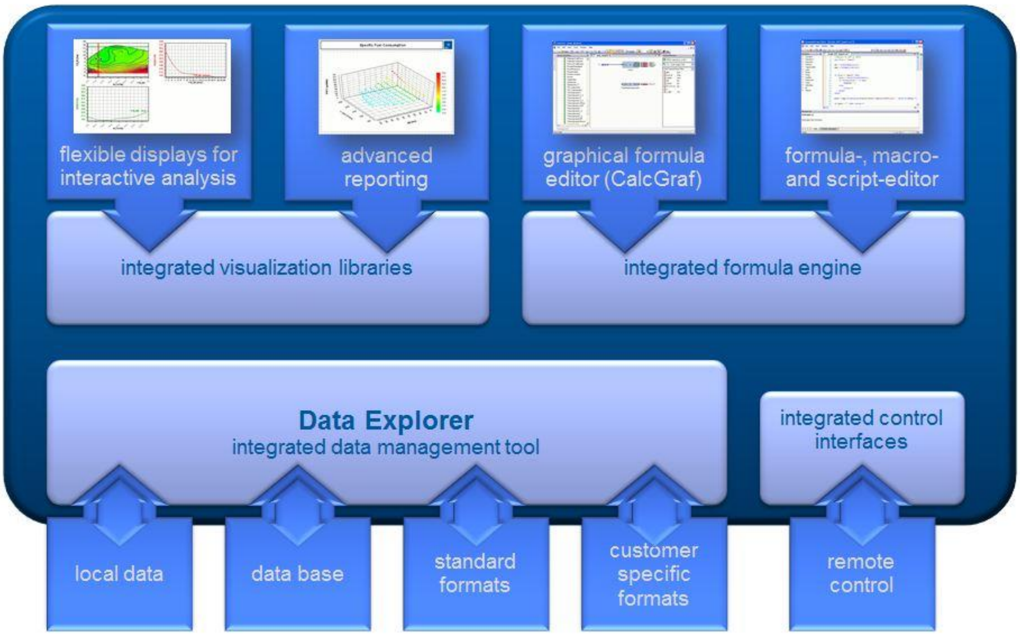


Figure 4.1: AVL Concerto - overview of product features and interfaces

4.4.2 AVL Cameo™

AVL Cameo is a complete software tool and environment originally marketed for engine mapping and calibration tasks. The software supports the complete workflow of designing an experimental approach, data gathering and analysis, modelling, optimisation and engine map generation. However, the software has evolved over time and is now applicable in all areas where Design-of-Experiment (DoE) and model-based approaches in development are required, or could be employed. The software supports many standard DoE approaches, as well as several modelling types in order to produce high quality models and response surfaces. The product model and workflow alignment are shown in Figure 4.2

For the purpose of this thesis, the main Cameo functions required and utilised were the DoE designer and test generator, along with the model generation capability. The model response surface visualisation and model quality metrics were also important attributes.

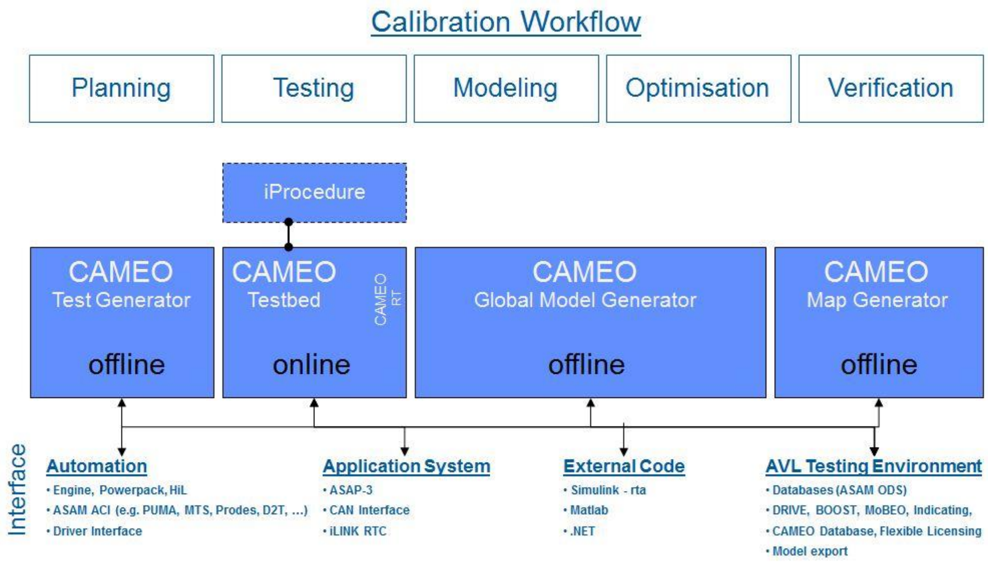


Figure 4.2: AVL Cameo - product main features and alignment with calibration workflow

4.5 Simulation environment (AVL Concerto^{TM})

In order to start the process of developing objective, combustion data quality metrics a suitable offline simulation environment was created to introduce errors into combustion data of known good quality - by which the response of any developed metrics could be observed and measured.

4.5.1 Error simulation

Using the Concerto programming interface, a macro function was created which allowed the possibility of shifting the measured pressure curve dataset, relative to the zero level axis. The input dialogue window to this macro is as shown in Figure 4.3, the program code in full is shown as Appendix A. In addition, this macro also included the possibility of applying an offset to the volume dataset relative to the reference TDC position. Together this provided the possibility to shift the pressure and volume table in along x and y axis. The macro produces a new, modified virtual data set (with offsets applied) that could be used in subsequent calculations. The effect of this macro function for modified and original pressure and volume is shown in Figure 4.4.

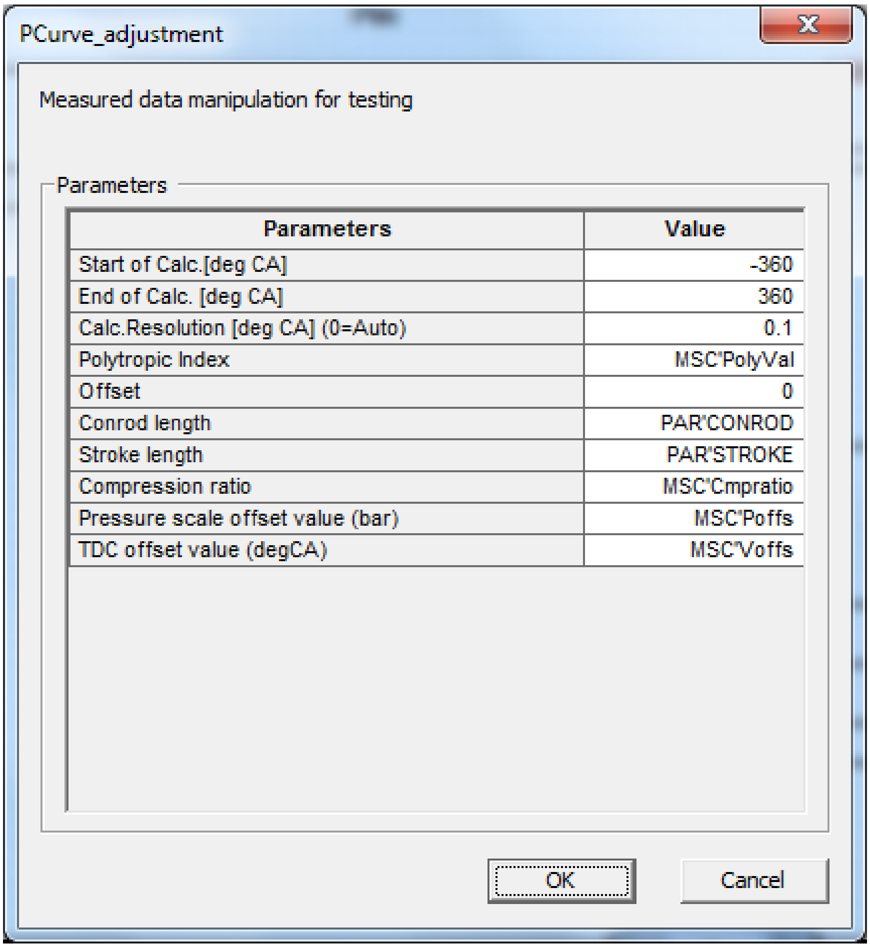


Figure 4.3: Input dialogue window for Pressure curves adjustment macro function

It was also necessary to be able to modify the compression ratio and polytropic scalar values included in the measurement data sets. This was executed via the creation of new, global data set scalar values for compression ratio and polytropic values, the new value consisted of the original value, with an offset applied. These values are available for any subsequent calculations and could be addressed and modified from the Concerto user interface, via appropriate display objects (Figure 4.5).

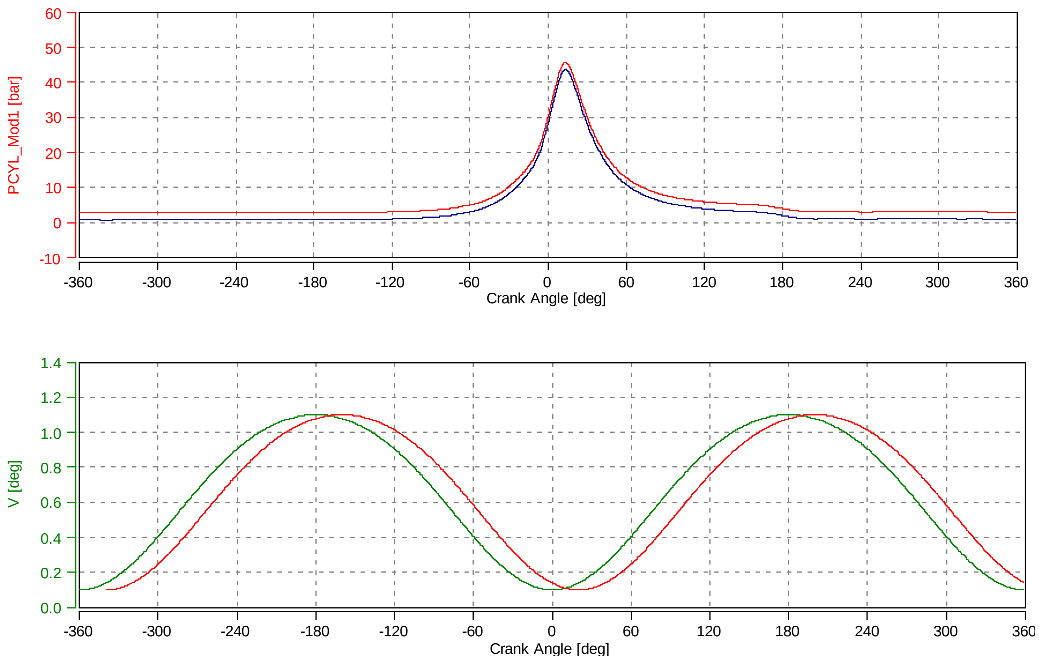


Figure 4.4: Display window showing original pressure and volume dataset, compared to modified virtual datasets from the macro developed for the simulation environment.

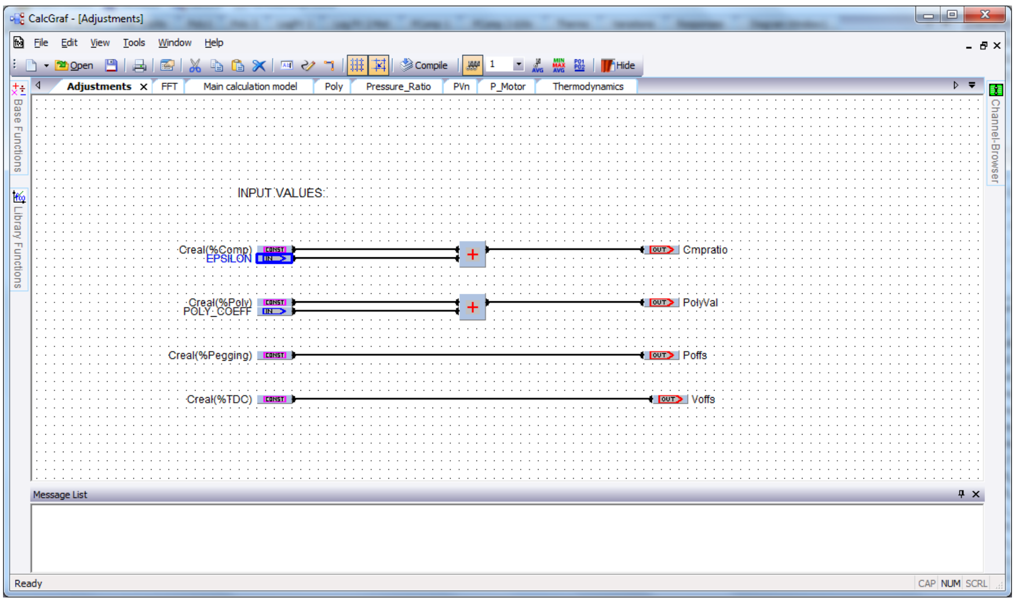


Figure 4.5: Calculation model developed using graphical formula editor in order to address and manipulate the required error variation parameters

The above configuration allowed a simulation environment to manipulate raw IFile data in order to introduce the required errors into measurement data that was otherwise of good quality. This facilitated direct comparison of good and poor quality data simultaneously. In addition, the errors could be varied (with respect to magnitude) in the user interface with appropriate display objects (sliders and input dialogues) which enabled visualisation of the effect of the errors on any calculated or derived results as shown in Figure 4.6.

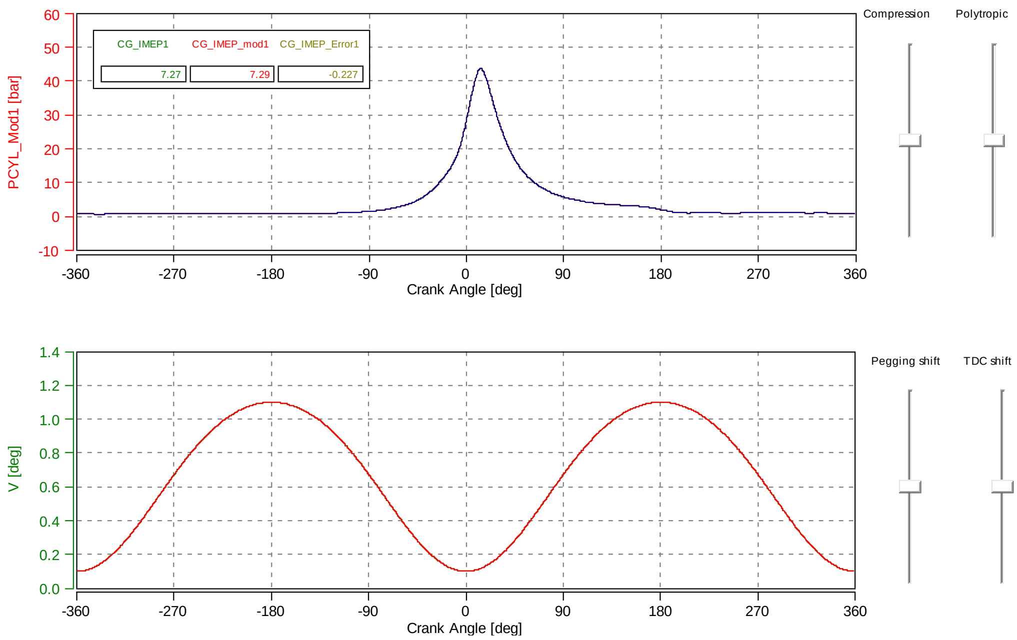


Figure 4.6: Display window showing raw data, in addition, slider objects are used in the display in order to be able to manipulate the error curves, and to be able to see responses immediately in the display

This environment provided sufficient flexibility to develop specific result calculations that can be used in the analysis. The requirement is to find results with sufficient response characteristics to the errors inputs when varied.

At this stage, averaged cylinder pressure was used in development. The reason being that cycle data is only really necessary where cylinder-to-cylinder, or cycle-to-cycle variations, need to be observed. The focus of this work is to be able to develop a reliable quality metric that can be applied even on a single cycle of data, meaning that large data sets or statistical information over a measurement period are not required for this work. Also, it is often the case in practice that single, averaged cycles are used where steady-state information or data is required in post-processing. The reason being that averaged data sets are more representative of a single operating condition, also they often suffer with less signal noise - due to the averaging process. If the developed metric can be successfully applied to a single cycle, then it can also be applied to data sets with multiple cycles and it can also be used to identify problem cycles in a full, cyclic measurement dataset.

4.5.2 Simulation tests

The developed results, or output responses needed to be analysed with respect to the magnitude of the output - compared to stimulation from the variation inputs. Initially the results could be observed manually in the graphical displays of the simulation environment. Curves could be compared and overlaid such that outputs with little or no response could be discounted at the initial stage. Whereas, outputs with an appropriate behaviour, could be shortlisted for further testing (Figure 4.7).

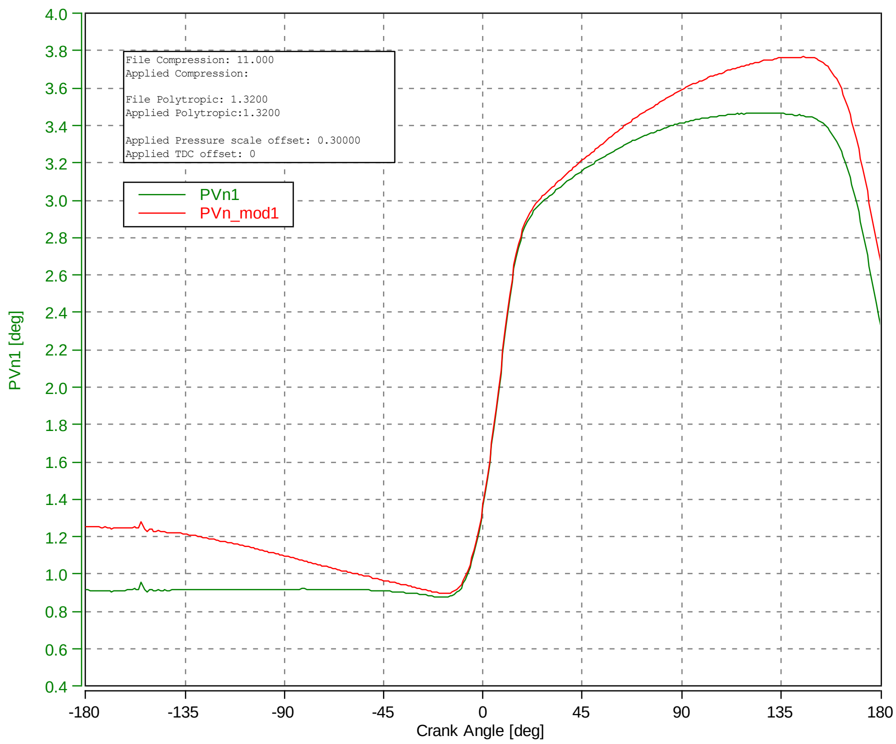


Figure 4.7: Initially, curves were manipulated and responses observed visually, comparing with standard, un-manipulated data, to allow filtering of suitable metrics for deeper analysis

Several curves of interest were utilised for the development of result metric responses, some of these were standard curves encountered in normal combustion measurement data analysis. In addition, further curves were developed in order to focus on specific areas of interest, with respect to the input variations. The main curves of focus were:

- Heat release curves, calculated based on a simplified algorithm using first law and a fixed gamma
- Process constant (PV^n=C)
- Polytropic exponent vs. crank angle

- Log Pressure – log Volume diagram
- Calculated compression curves

In addition, further curves were derived in order to gain a deeper understanding of the responses of the curves to stimulation from the variation parameters, these additional calculations were:

- Fast Fourier Transform
- Integrals
- Derivations (1st and 2nd order)

Many of the standard calculations provided in the software were useable for creating the benchmark, comparison curves and results. However, some of these result calculations had to be modified so that they could be manipulated with respect to the volume table input, as well as the parameters for compression and polytropic, where these are used in the calculation and normally gained from the measurement file parameters.

Particularly, macros involving calculations where a volume table is required needed to be re-written and adapted. An example is shown in Figure 4.8 for a macro which calculates an extrapolated compression curve.

Macro Function: CompressionCurve_mod.mac | Macro Function: Compre

```
//_comment = Extrapolated Compression Curve
//_comp = Alg.|Compression Curve (A)
//_src1 = SourceSignal|PCYL
//_src2 = Source Signal|VMOD
//_defnames = Pcomp
//_start = Start Angle [grd CA]
//_poly = Polytropic Coeff.

arg _src1, _src2, _comp=0, _start=-20, _poly=1.32

P=range(_src1,-180,180,1)
Vol=range(_src2,-180,180,1)

for i= (_start+181) to 361
  P.y[i]=P.y[i-1]*pow(Vol.y[i-1]/Vol.y[i],_poly)
next

return P

```

Figure 4.8: Example macro code showing volume table call

On the left side, the macro function code shows that in line 11, the dataset ‘V’ is called and used in the calculation, on the right hand side the modified version uses an additional input dataset, known as _src2. This is defined in the macro header and creates an additional input terminal to the macro where an external input for a volume calculation can be used. The macros appear in the user interface as shown in Figure 4.9.

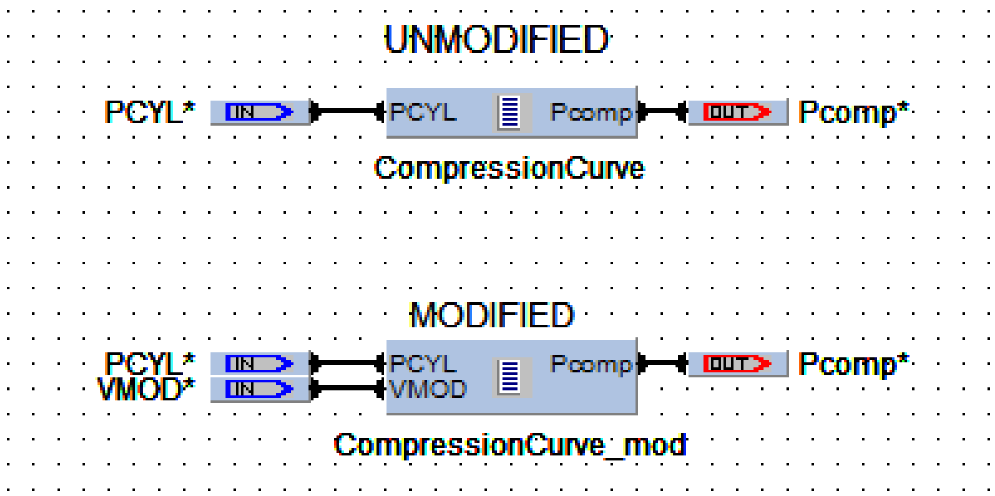


Figure 4.9: Macros, modified and un-modified – modified for input from an external dataset that calculates cylinder volume

Several standard macros had to be modified in this way to achieve the correct curves for comparison in the simulation environment. Once the required curves were created, it was then possible to develop a set of result calculations from these curves, which could then be assessed for suitability and processed further.

Some new results could be derived using the standard library of functions provided, in combination with the model based complier for nesting calculations, available in the Concerto software. However, in several cases, it was necessary to develop new result calculations, this feature being supported in the user interface.

Figure 4.10 shows one of the calculation models that were built up using the graphical editor. This calculation model delivers standard and modified curves and results for the normal and modified datasets, with typical curves/results derived from the pressure curves, so they can be compared directly. Note that an example of a macro (function block) that was created has been mentioned previously and the code is shown in Appendix A.

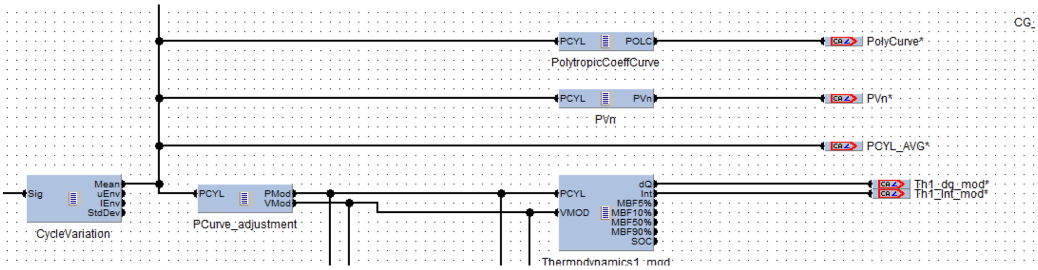


Figure 4.10: Calculation model shown in the graphical user interface (CalcGraf) for the calculation of curves and results

Once the curves and an initial set of results were created, these could then be observed and compared visually in the user interface. The table in Appendix C shows all the curves and results which were created.

4.6 Modelling and experiment definition (AVL Cameo)

During the simulation phase, there were a number of data sets which needed to be evaluated with respect to variation parameters – compression, polytropic, TDC and Pressure scale offset and then evaluate the responses.

This involved loading test datasets, then varying the inputs, saving and exploring the data in order to evaluate the outputs objectively, to be able to develop conclusions about the validity of the results and their feasibility for further usage. There are a number of issues that could occur, depending upon the approach:

- Manual execution of a measurement and evaluation routine is a repetitive task which is a considerable risk from human error when a large number of interactions are to be executed – there is a possibility of mistakes and errors in recorded data, or the procedures used for measurement
- Executing a large number of measurement points/iterations is very time consuming

In this instance it was decided to use the following approaches to counter the risks to data quality and repeatability:

- To use an automation script, this would load the data set, adjust the variation parameters, record the results and produce an export file for analysis. Using this automated approach would considerably reduce the test time, and vastly reduce the risk of errors in the data or the procedure.
- A DOE (Design-of-experiment) procedure was used in order to reduce the number of test points required. In general, this involves using a strategically gathered set of measurement points in order to build a mathematical model or function, of the response output relative to stimulation from variation of input parameters.

4.7 Design of experiment (DoE) approaches

DoE based test approaches are widely used in industry to decrease the number of measurement points and increase efficiency in testing procedures. In a typical process, at the beginning, an experiment plan is defined with which data are obtained for building of response models.

The goal of a model based approach is the evaluation and optimisation of a system behaviour – and determination of the input variables that lead to optimal output variables (maximum performance, minimum consumption/emission).

There are numerous approaches to DoE based testing, each have their own advantages and disadvantages, and some approaches are simply developments of others. Below is a summary of the most commonly encountered methods:

4.7.1 Full factorial

This design contains all possible combinations of a set of variations, as shown in Figure 4.11. Full factorial designs are the most conservative of all design types. The number of design points grows exponentially in the number of variations, so full factorial designs may be too time-consuming to run for many purposes.

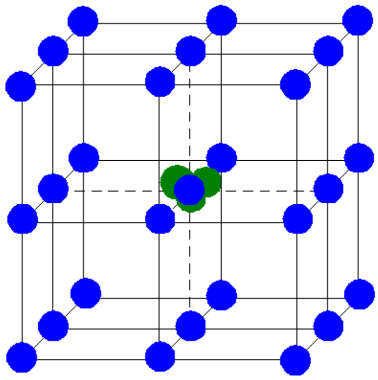


Figure 4.11: Full factorial - different factor layers for different variation parameters are possible, no central point is used

In general, these designs are used for preliminary investigations - to get an overview at the project start. Note that this is not really a DoE approach, as measurements are made across the whole design space.

4.7.2 Central composite

Central composite designs are response surface designs that are used for quadratic models describing the quantitative dependencies of one or more target quantities, from a few influencing quantities or factors as represented in Figure 4.12.

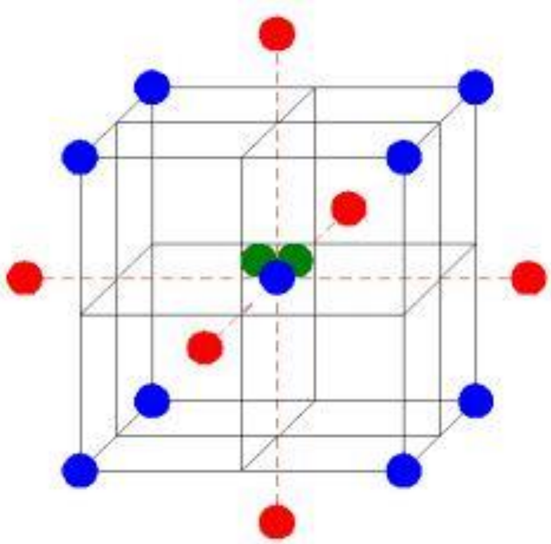


Figure 4.12: Red points are axial points and identify the "star" and therefore are called star points. Green points identify the centre and possibly repeated points. Blue points are corner points and identify factorial points.

Central composite designs are orthogonal designs of the advantage that there is no interdependency between estimates for model coefficients, i.e. they do not affect each other. Also, confidence intervals are as narrow as possible due to a given number of repetitions.

4.7.3 Box Behnken

Box-Behnken designs are a selection of 3^n factor level combinations of a full factorial design. Figure 4.13 shows the positioning of individual runs for three variations:

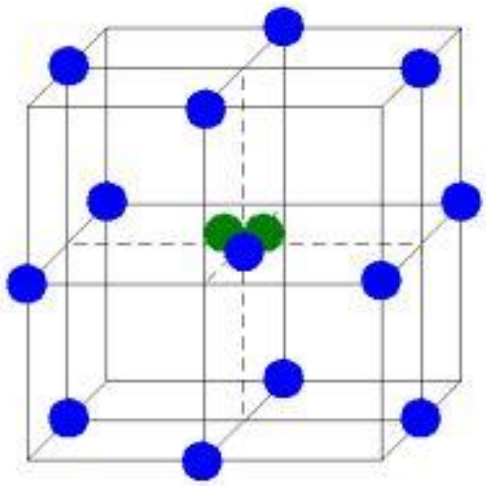


Figure 4.13: Green points identify the centre and possibly repeated points. Blue points are factorial points

They are based on 3-level Full-Factorial design vertices and central points of the faces are skipped. They are reasonable to use in application up to a maximum of 4 variation parameters. Above that, the number of required tests Box-Behnken Design would be too large.

4.7.4 D-optimal

D-Optimal designs are generated by the computer and choose, at random, the number of factor level combinations from a set of candidate points. The points are distributed with the goal to maximize the volume of the design space and to minimize the interaction between individual points (Figure 4.14).

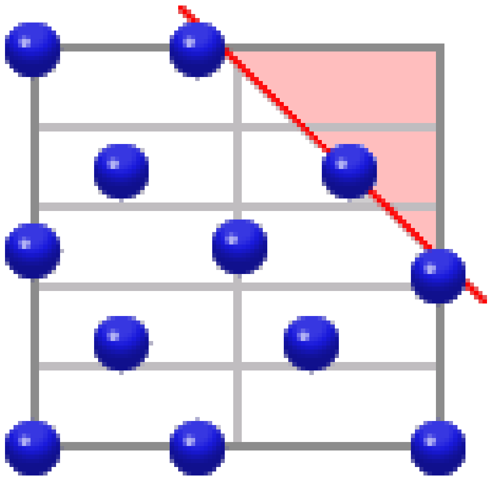


Figure 4.14: D-Optimal design: The red surface identifies the design space. Blue points are factorial points

Note that this design is also applicable to higher-order polynomial models. Different model orders for different variation parameters are possible as well as inclusions. Any experimental space can be employed in this design.

4.7.5 Latin hyper cube

Latin Hypercube Sampling designs are sets of n design points that project onto n different levels in each factor, as shown in Figure 4.15. Here the points are generated randomly, i.e. the sequence is determined by means of random numbers.

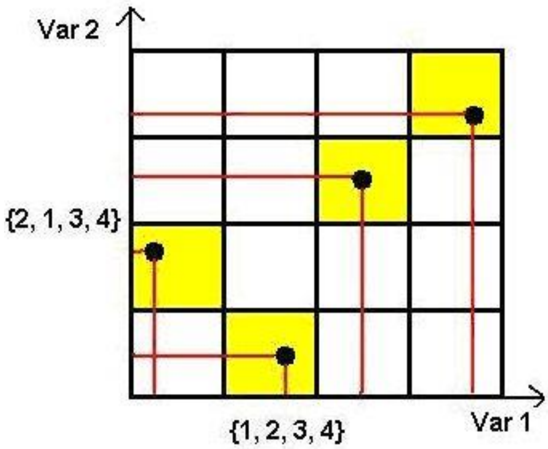


Figure 4.15: Latin Hypercube Sampling design with 4 points in a 2D design space:

This design is "space filling" type – these designs are used if there is little or no information about underlying effects of factors on responses. Space-filling plans are characterised by an even distribution of the measuring points in the parameter space and an optimal coverage of all parameter levels.

4.7.6 SOBOL

This design uses a quasi-random algorithm and distributes the design point uniformly over the design hypercube, as shown in Figure 4.16.

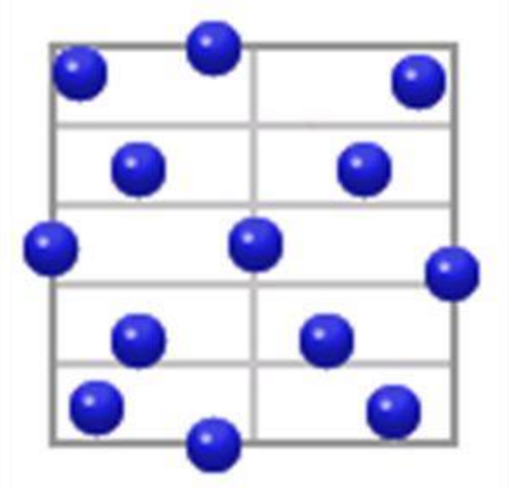


Figure 4.16: SOBOL - Quasi-random, space-filling design

For this design, in common with other space filling types, no previous knowledge about the system to be measured is required, and the data gained are generally well suited for model training.

4.8 DoE method

It was decided to employ a DoE approach for gaining the measurement data from the simulation environment to reduce test time for the numerous iterations needed to create the required data sets. Generally speaking, this is not absolutely necessary as simulation time is normally inexpensive when compared to the time required to execute tests in a physical environment. However, the general trend in industry is to 'frontload' and move many tasks towards simulation. This increases the complexity of a given simulation environment, also the costs with respect to time. Therefore, DoE in simulation is an emerging requirement and hence the approach is validated in this work.

Considering the background of combustion measurement and data, it was considered that the data/models would not be of significant complexity – so that sophisticated modelling techniques would not be required. It was considered highly likely that the response surfaces would be simple single or 2nd order polynomial functions – hence a low order polynomial model would be very appropriate - with respect to performance and complexity/calculation time. However, to protect for unforeseen effects, also, to widen the scope of this work. It was decided to measure some additional data using alternative approaches. In summary:

- D-Optimal design was chosen for model training, this design is well established and used in industry. It shows good performance for modelling polynomial responses and focuses measurement points in the centre and at borderlines – ideally for fitting low order functions.
- Full factorial design was used to create some datasets but these would only be used for comparison purposes – this was possible due to the short measurement time in the simulation environment. Note that this design was not used in the physical test environment as it would be far too time consuming.
- SOBOL design was used to create additional data for measurement quality assessment. Data gathered using this stochastic method was used to compare with the model based data.

4.9 Implementation of the DoE (AVL Cameo™)

In order to reduce the number of test points, an experimental approach was designed that could be incorporated in the automation procedure. The variations required were quite simplistic, due the nature of the datasets, it was not expected that there would be any complex interactions so a simple test design could be employed. The D-optimal was chosen as the nature of the model responses were expected to be linear or polynomial (not with high order). The basic concept of this design is that test points are generated by the computer and chosen at random. The number of factor level combinations are derived from a set of candidate points. The points are distributed with the goal to maximize the volume of the design space and to minimize the interaction between individual points as shown in Figure 4.14.

Starting from an initial value (that can be specified), statistically computed points are measured. The D-Optimal algorithm adjusts the position of these points to the design space until the required fit is achieved. The number of variation points depends on the model order.

Using the test designer in the AVL Cameo tool, a D-optimal approach produced the variation test run points which needed to be run for the modelling, with measurements from each output result measured and stored appropriately by the automation script. In all 42 test points were required and these are shown in the table in Appendix D. This test variation data, generated using Cameo, was stored as a standard text file format, ready to be imported into the Concerto test script for execution, where the measurement would be taken and then stored in another data text file.

4.10 Automation of testing (AVL Concerto^{TM})

Once the test points had been defined, the test run could be executed using the developed automation script. The Concerto tool has an in-built scripting interface which allows automation of typical data processing tasks. This interface uses a high-level scripting language based on Visual BASIC. The script was developed and de-bugged over a number of iterations and tests. The final working version is shown in Appendix B. This script allowed very easy processing of multiple data sets, also decreasing the risk of errors and improving the quantative reliability of the datasets that were gathered.

Once the script was activated in the simulation environment, the variations and measurements would be made, with all data being written to a text file ready for storage and further processing. The basic requirement for the automation task is shown below in Figure 4.17:

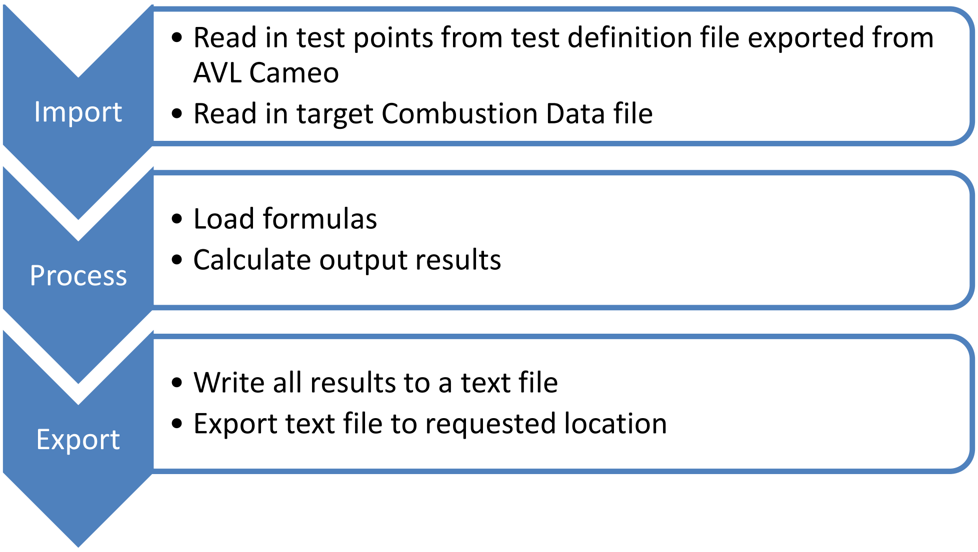


Figure 4.17: Basic workflow of automation script

The script was designed to use the Concerto user interface objects. Figure 4.18 below shows the main user view. Employing the data explorer tool within Concerto, it was necessary to define the test script to be used, also the target data file (in AVL IFile format) onto which simulated errors would be applied. These are seen with the appropriate file aliases ASCII1 and IFile1.

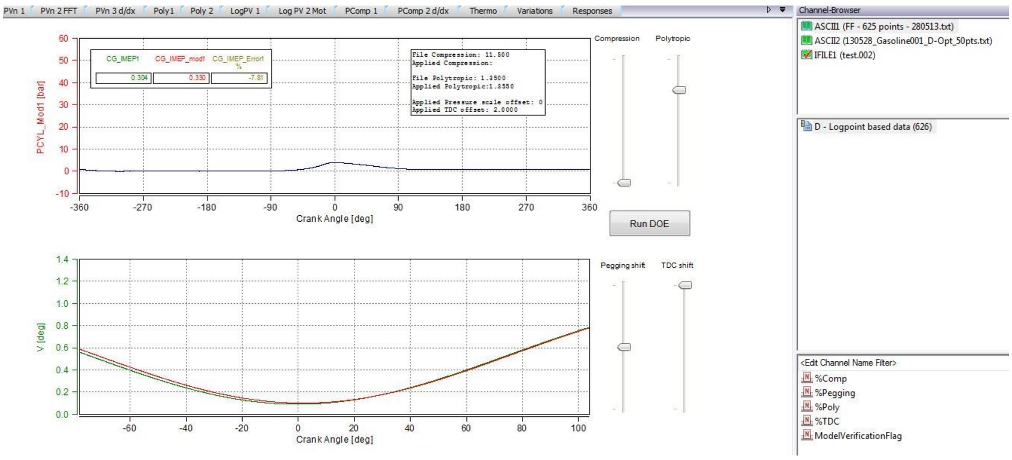


Figure 4.18: Script user interface within Concerto

The ascii file is the file created by the Cameo DoE designer, this file defines the required measurement points. It forms a variation test list, and example is shown below in Figure 4.19

LogPt	%Comp	%Pegging	%Poly	%TDC
1.00	0.0000	0.0000	0.000000	0.0000
2.00	1.0000	0.0000	-0.010000	0.0000
3.00	0.0000	-1.0000	-0.005000	-1.0000
4.00	1.0000	2.0000	0.005000	-1.0000
5.00	-1.0000	0.0000	0.010000	1.0000
6.00	-0.5000	-2.0000	0.000000	1.0000
7.00	1.0000	1.0000	-0.005000	0.0000
8.00	0.5000	0.0000	-0.005000	-1.0000
9.00	1.0000	2.0000	-0.005000	1.0000
10.00	-1.0000	1.0000	0.000000	0.0000
11.00	0.0000	1.0000	0.005000	2.0000
12.00	-0.5000	2.0000	0.010000	-2.0000
13.00	0.5000	-2.0000	-0.010000	0.0000
14.00	1.0000	0.0000	-0.010000	-1.0000
15.00	0.5000	-2.0000	-0.005000	1.0000
16.00	0.0000	1.0000	0.010000	-1.0000

Figure 4.19: Variation list used by the simulation to gain test data for model training

Once the target data file and test variation lists have been selected, the script is activated by a simple user push button. This opens a further dialogue for the user to select the destination and file name – on completing this action, the script is executed. In simple terms, the process is:

- The required measurement conditions are set, according to the variation parameters of compression ratio, pegging, polytropic and TDC. Specifically, for each of these values, the value in the source data file has the offset applied – that is, each of the values is distorted by the offset value in order to create the error data set.
- Once all offsets are applied, the calculations which have been developed and are under observation are run, creating a new set of results from the error induced data.
- These results are collated together and written as a line in a report window, with output results that correspond to a given set of error states.
- The script then moves to the next operating point step (as defined in the variation list), recalculates the results, then writes a new, corresponding line of results in the report window.
- Once all points have been executed, the report window is then exported as a text file and saved in the defined location.

- This creates a text file with columns of variation setting and corresponding results (File alias - ASCII2). This file can then be imported into the modelling environment for further processing. A typical file is shown in Figure 4.20 below.

1 | PVn 2 FFT | PVn 3 d/dx | Poly1 | Poly 2 | LogPV 1 | Log PV 2 Mot | PComp 1 | PComp 2 d/dx | Thermo | Variations

CG_IMEP1	CG_IMEP_Error1	CG_IMEP_mod1	CG_PMEP1	CG_PMEP_Error1	CG_PMEP_mod1	Cmpratio	Comp E:
7.2698	-0.2271	7.2863	7.2698	-0.2271	7.2863	11.000	0.0000
7.2698	-9.2105	7.9394	7.2698	-9.2105	7.9394	12.000	1.0000
7.2698	8.9191	6.6214	7.2698	8.9191	6.6214	12.000	1.0000
7.2698	-9.2145	7.9397	7.2698	-9.2145	7.9397	10.800	-0.2000
7.2698	-9.2145	7.9397	7.2698	-9.2145	7.9397	12.000	1.0000
7.2698	8.9191	6.6214	7.2698	8.9191	6.6214	11.200	0.2000
7.2698	-9.2078	7.9392	7.2698	-9.2078	7.9392	11.000	0.0000
7.2698	8.9191	6.6214	7.2698	8.9191	6.6214	10.000	-1.0000
7.2698	5.2429	6.8887	7.2698	5.2429	6.8887	12.000	1.0000
7.2698	8.9255	6.6210	7.2698	8.9255	6.6210	10.000	-1.0000
7.2698	-1.1317	7.3521	7.2698	-1.1317	7.3521	12.000	1.0000
7.2698	-8.3193	7.8746	7.2698	-8.3193	7.8746	10.000	-1.0000
7.2698	-8.3193	7.8746	7.2698	-8.3193	7.8746	12.000	1.0000
7.2698	-0.2271	7.2863	7.2698	-0.2271	7.2863	12.000	1.0000
7.2698	8.9258	6.6209	7.2698	8.9258	6.6209	11.000	0.0000
7.2698	-9.2145	7.9397	7.2698	-9.2145	7.9397	12.000	1.0000
7.2698	-9.2115	7.9395	7.2698	-9.2115	7.9395	10.000	-1.0000
7.2698	8.9221	6.6212	7.2698	8.9221	6.6212	12.000	1.0000
7.2698	8.9258	6.6209	7.2698	8.9258	6.6209	12.000	1.0000
7.2698	-9.2145	7.9397	7.2698	-9.2145	7.9397	10.000	-1.0000
7.2698	8.9258	6.6209	7.2698	8.9258	6.6209	12.000	1.0000
7.2698	-0.2271	7.2863	7.2698	-0.2271	7.2863	10.000	-1.0000

Figure 4.20: Output file from the simulation, variations and responses, in columns, ready for modelling

4.11 Verification test (engine test bed)

This test plan will provide sample data suitable for verifying the simulation environment used to create and test the Data Quality Metrics. Once the metrics have been developed and proven in an offline environment. This data will be used to verify the correct, appropriate response and sensitivity of the metrics.

The data sets required will consist of:

- Good quality measurement data, with no errors
- Good quality measurement data, with induced errors of:
  - Static Parameter errors
    - Polytropic
    - Compression ratio
  - Dynamic errors
    - Pressure scale error +/- offset
    - TDC error +/- offset

For the purpose of this work, it is only necessary to measure the data from a single cylinder. It is suggested to use the instrumented cylinder which is closest to the angle encoder position, to avoid any errors due to torsional vibration effects at engine and dynamometer mechanical system critical frequencies. The following test plan is suggested:

4.11.1 Test equipment and environment

The test environment used to collect the data for validating the simulation environment was the engine test facility located at the University of Bradford (Hyper – C). This test bed is typical of such an environment used in industry for engine development and research. The test environment broadly consists of:

1. An gasoline engine, 5.0 V8, this engine was available and suitable as a typical test specimen, specifications as follows:

Engine type/fuel	Gasoline, 4 valves/cylinder Direct fuel injection
Displacement/cylinder	625cc
Bore/Stroke	92.5/93.0
Cylinder number	8
Compression ratio	11.5

2. A Dynamometer – AVL APA type, active 2 quadrant machine with 200kW absorption capability
3. AVL PUMA test control and data acquisition software
4. AVL Indismart 8 channel combustion analyser complete with AVL 365 front end mounted angle encoder.
5. Horiba MEXA 7000 – 4 channel raw gas emissions bench

For this experimental work, the most important equipment was the engine and pressure measurement chain as follows:

- Engine was equipped with a directly mounted cylinder pressure transducer, diaphragm located in the combustion chamber, close to the cylinder wall for good knock signature recognition – not relevant for this test work but nevertheless, this is still a good position to gain a representative cylinder pressure.

- The transducer was a Kistler 8mm type, uncooled. Mounted in a purpose made adaptor to provide good sealing and isolation from mounting strains and operational stresses that could affect the measurement accuracy under certain conditions.
- The angle encoder was mounted on the engine FEAD pulley via a rigid adaptor interface, with torque reaction lever mounted to the engine block
- The above mentioned components were connected to the measurement device, located in the test cell, close to the engine.

In order to ensure accurate acquisition of the validation data, a number of precautions and observations were made:

- Transducer installation was pre-checked, transducer was removed and cleaned ultrasonically prior to the test work. The transducer was carefully installed according to manufacturer instructions, the sensor was installed with a suitable torque wrench to minimise mounting stress
- All cabling was carefully routed in isolation to avoid possible noise and cross talk. Cable and connectors were cleaned with solvent prior to assembly. Electrical ground bonding was checked visually and using a test meter to ensure a high integrity ground between, measurement device (which incorporates the signal charge amplifiers), engine, engine mounting system and baseplate
- The measurement device was located inside the actual test cell, as close as possible to the engine to ensure short cable runs for the charge signal cables
- The encoder mounting system was double checked prior to the start of test, the signal transmission was via fibre optic/LVDS to ensure highest quality and common mode rejection of signal noise. The target cylinder for data acquisition was that closest to the angle encoder location to reduce errors due to torsional effects of the crankshaft system.

- The complete ‘system’ was calibrated using the ‘dead weight’ method and equipment. This allows full calibration of the whole measurement chain – sensor, cabling, charge amplifier and measurement system analogue-to-digital converter (ADC). This procedure was undertaken prior to start of the measurement series.
- Once installed, the system was checked as stated in the following section. The data was collected in one day to ensure minimal effect of the changing ambient conditions. Also to ensure minimal disturbance to the test environment (including drift effects that can in measurement systems occur over longer periods)
- All of the collected data would be averaged in order to process and compare with the simulation environment. However a statistically valid number of engine cycles had to be gained for each measurement condition. Based on the authors experience this was as follows:
    - Idle data – is always quite unstable due to inefficient flow and breathing in-cylinder conditions, as this data was expected to have high cyclic variation just 100 cycles were measured with an acceptance of the above factor. Obviously, the time taken to collect the cycles at low speed is longer, so 100 cycles was considered sufficient in order to reduce the time taken at this operating point.
    - Motored - Most of the variation effects in combustion data occur during fired operation, this is where in-cylinder conditions vary significantly form cycle-to-cycle due to combustion and flow conditions. Therefore, 100 cycles of motored data was sufficient to provide a good quality mean cycle. CoV of IMEP was used as a stability indicator with a threshold of 2% being a maximum limit
    - Fired – This condition needs more cycles in order to gain a statistically valid mean cycle, due to the cycle variability inherent in gasoline combustion. However, this fact also has to be traded off, or at least considered with respect to measurement time. A suitable compromise for this exercise

was considered to be 300 engine cycles with a maximum CoV IMEP of 4% for the dataset

4.11.2 Pre-test checks:

- Load correct parameter file for the engine and measurement task
- Confirm correct parameterisation of the complete system in Indipar (measurement parameterisation software). Paying particular attention to:
    - Correct amplifier settings – scaling, drift compensation
    - Double check of amplifier settings against parameter settings in Indicom (bar/V scaling)
    - Correct zero level correction method (thermodynamic)
    - Check engine geometry is correctly parameterised
    - Check polytropic exponent is correct assigned according to engine type
    - Physical check of encoder mounting and security prior to engine start
    - Physical check of transducer wiring interface between transducer and charge amplifier
    - TDC calibration as described in Appendix F

4.11.3 Measurement procedure

In order to collect data with the defined errors, then to be able to examine the effects and interactions of these errors, the proposal is to measure the data in groups, with each of the target errors induced in each case. For example, a collection of data sets with TDC errors, a collection of datasets with polytropic errors etc.

As the errors in each case have a predictable response with respect to variation. Also, taking into account the model based approach used to analyse the errors, it is proposed to measure at the extreme limits of the error stimulation, with one measurement in the centre position. For example - Measure at -2 degrees TDC error, 0 degrees, and + 2 degrees error. This centre position is effectively a ‘no error’ condition and can therefore be used as a verification data point – for correlation with a known ‘good quality’ dataset.

In addition, this approach reduces the number of measurement required at the test bed, but will correlate well with the D-Optimal test design used in the simulation environment. As this test design tends to use measurements at the extremes and central areas of the design space, in order to create well-fitting models with low order functions. The measurement procedure was followed as defined below, in the order prescribed, as a single measurement series/procedure. Where possible, engine downtime between tests was avoided to minimise the impact of system drift and to maximise repeatability in the data:

4.11.4 Test plan overview

Figure 4.21 is a graphical representation of the test procedure, used at the test bed, in order to measure the verification data. The individual process steps are describe in detail in Appendix E. The engine was fully warmed up to normal operating temperature prior to the start of the measurement procedure.

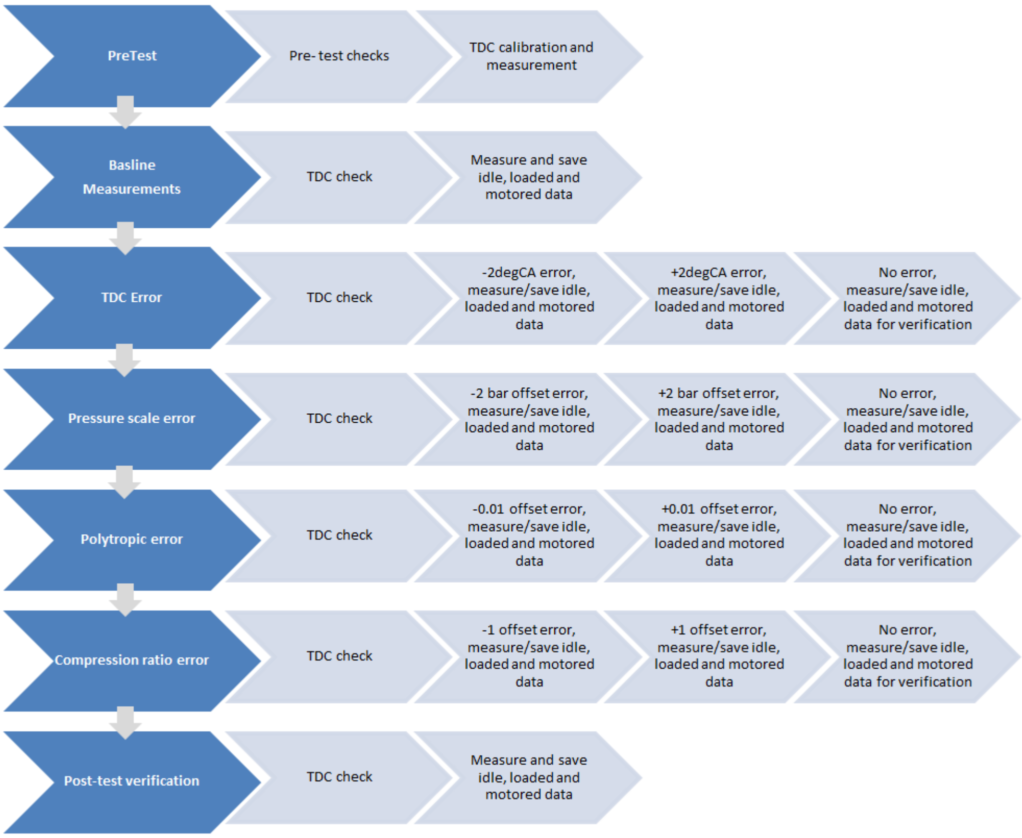


Figure 4.21: Test procedure for verification data from the engine test bed - for verification of the simulation

4.12 Summary

The script was successfully used to create numerous data sets that were used to verify the operation and reliability of the environment. As well as for creating all the data needed for modelling and verification. Automation of this procedure improved the speed of executing this procedure, and the reliability of the data produced. In addition, the ability to use a single working environment (i.e. Concerto) was a great asset in this instance as it reduced the number of interface points in the workflow process, this reducing the risk of compromised data quality.

The DoE based test planning reduced the number of test points, and in combination with the automation proved to be a very productive environment for this work. The verification tests were considered to be critical – in order to validate the offline based activities, as well as to verify the data being generated by the simulation environment. An essential part of this physical testing was a very clearly defined process, with appropriate procedures to ensure data consistency and quality – in order to be able to provide reliable data from a traceable and reproducible source.

5 Results and analysis

In this chapter, the results from the various test environments and analysed in detail and compared. The raw data is first examined and statements derived regarding the quality of this data with respect to accuracy, repeatability and other factors such as noise.

For the simulation and modelling environment, an analysis of the different modelling approaches is discussed, as they are compared against each other. From this, a single, best approach is defined and this is used as the basis to create data sets from which decisions are made with respect to the results which perform with the greatest and most reliable response, with respect to applied variations. From this data, a short list of suitable results is defined, bearing in mind the key variation parameters.

The shortlisted result parameters are then taken forward for the verification testing. The measured results, from actual 'on test bed' data is then compared to the outcomes from the simulation environment. It is then possible to correlate the performance of the simulation with the real environment, also, it is possible to verify that the shortlisted results perform accurately in a real world application, where it can be proven and stated that they are useable for data quality assessment.

5.1 Initial data sources for experimentation

The data used in the simulation environment consisted of measurement data sets of known good quality, made under various different operating conditions, with different engine types. This produced a good cross-section of sample data for development of the metrics. Initially, the data was checked for accuracy and validity with respect to:

- Noise
- Repeatability
- Stability
- Quality

- Accuracy

Noise effects can identified via visual examination of the raw pressure curve data. Stability and accuracy can be established via close examination of key result parameters, in particular using statistical information from these parameters (variance, standard deviation). Once the data was confirmed as useable, it could then be ported into the simulation environment and used for development of the metrics

The data gathered from the test bed (Online – physical test) was subjected to a measurement procedure (documented in Chapter 4.11). This procedure was configured carefully to ensure consistency and accuracy. The accuracy of the TDC calibration was maintained by a repeating procedure to establish this before each measurement. In addition, motored curves were measured after each sequence as this provides data which can verify the TDC and scaling accuracy retrospectively at any point. In addition to this, a careful procedure was designated involving checking of the physical system set-up and parameterisation prior to measurement sequence start. The corresponding parameter files were stored with each measurement so that the exact system set up, at the time of the measurement, can be established in the data processing phase (as well as the data quality, and TDC/Scaling accuracy).

5.2 Method of data analysis from simulation environment

The simulation data was generated via an automation script, and then imported into the modelling tool to create simple 2nd order polynomial models from the strategic measurement points defined in the design of experiment (DoE) process. This allowed the creation of representative response surfaces which showed the relationship between outputs (the response of result parameters) compared to inputs (variation of the 4 main stimuli).

The model data can then be visualised in various ways to understand the sensitivity of any particular result output value, when compared to a variation of an input. The result outputs were grouped together logically in order to simplify the visualisation.

Several experimental approaches were chosen to gather the data, in order to make some comparisons between suitable DoE designs and modelling approaches. These are explained in detail in chapter 5, in summary, they were:

- Full Factorial – Design incorporates a large number of measurement points at all layers, all combinations.

- D-Optimal – A stochastic design approach which concentrates measurement points at the borders of the design space. The points are distributed with the goal to maximize the volume of the design space and to minimize the interaction between individual points.

- SOBOL – Another stochastic design that is characterised by an even distribution of the measuring points in the parameter space.

For each design, the automation script for the test plan was derived from the DOE wizard in the AVL Cameo user interface for each design. This was then exported as a text file, to be processed and executed via the automation script in the AVL Concerto tool. For the D-Optimal design, an additional number of repetition points are suggested and these were added to the basic measurement points calculated by the designer in the software. The configuration dialogue for the D-Optimal design is shown in Figure 5.1.

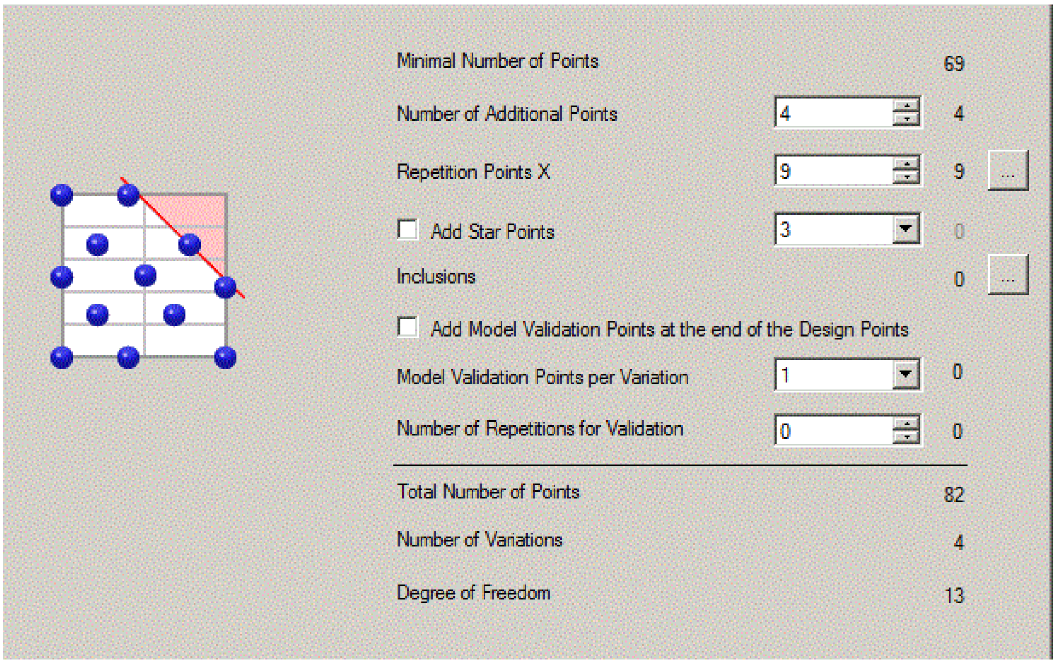


Figure 5.1: Configuration dialogue for D-Optimal design in Cameo

Once the script was executed, in each case, a data set was created with variation inputs and corresponding responses of the result outputs. These data sets could were then imported into Cameo for raw data quality checking prior to model building. Initially, the raw data needed appropriate analysis to ensure that the variations were executed as prescribed. Figure 5.2 shows data which has been measured within a D-Optimal design.

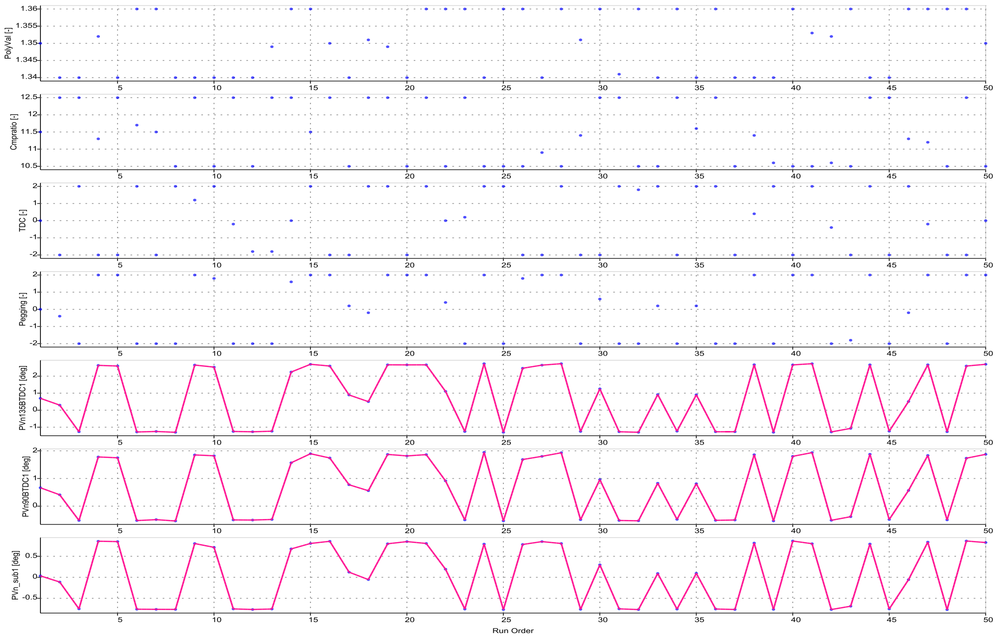


Figure 5.2: Raw data validation plot variation and responses against run order

The four variation parameters are shown against run order (top, PolyVal, Cmpratio, TDC, Pegging), the responses of PVn135BTDC1, PVn90BTDC1, PVn_sub1 are plotted against the same abscissa (bottom). The trend between variation and response can be immediately seen. In Figure 5.3, two sets of measurements are shown, in this case a D-optimal design was run first in order to gather data for model training, subsequently a SOBOL test design was executed in order to have additional data for model verification. The diagram shows variation versus run order for training (blue points) and verification data (green points). The green line over the training data shows the repetition points connected together, in this particular case, as this data is sourced via simulation; repetition monitoring is not really required (but could be useful). The fact that the line is perfectly horizontal shows that these points repeated exactly (to be expected).

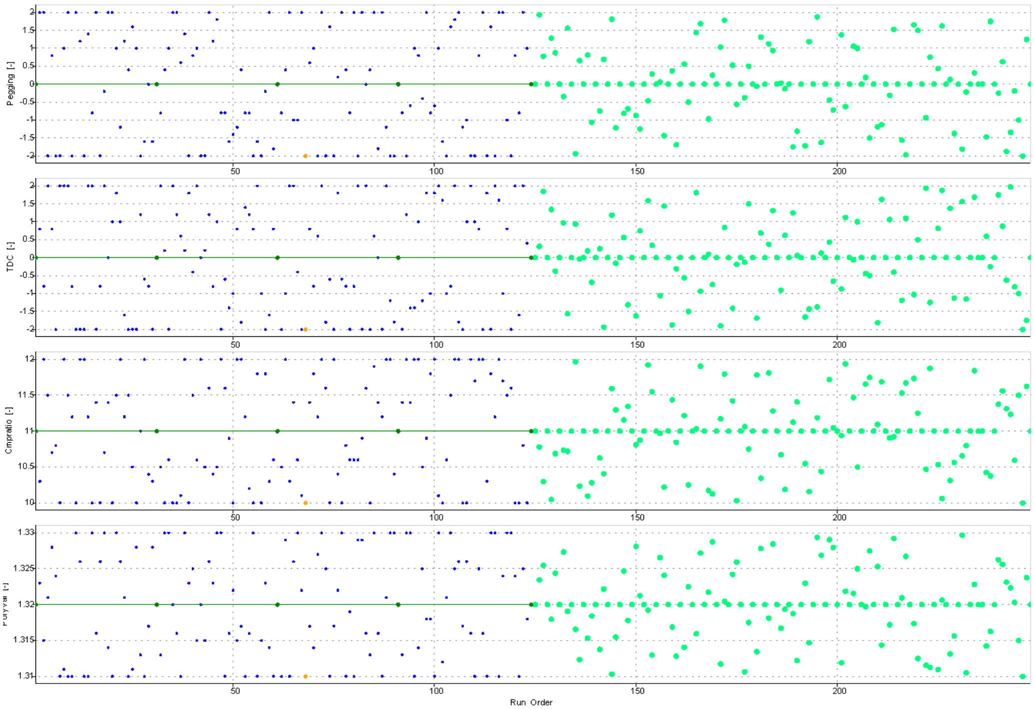


Figure 5.3: Variation vs. run order for D-Optimal training data and SOBOL verification (typical results shown)

The green measurement points are according to the SOBOL design, this graphic shows quite clearly how the D-Optimal design concentrates measurement points at the extremes and the centre, which is ideal for modelling via polynomial functions. Whereas, the SOBOL design has a greater, more random scattering of measurement points, this is less suitable for polynomial modelling and is more appropriate for complex model surfaces.

The data sets were also checked for rogue points and outliers, normally, this would not be expected to be an issue from simulation data, however, scanning the raw data showed one rouge point – this was identified and deactivated before any modelling was attempted. The raw data analysis dialogue is shown in Figure 5.4.

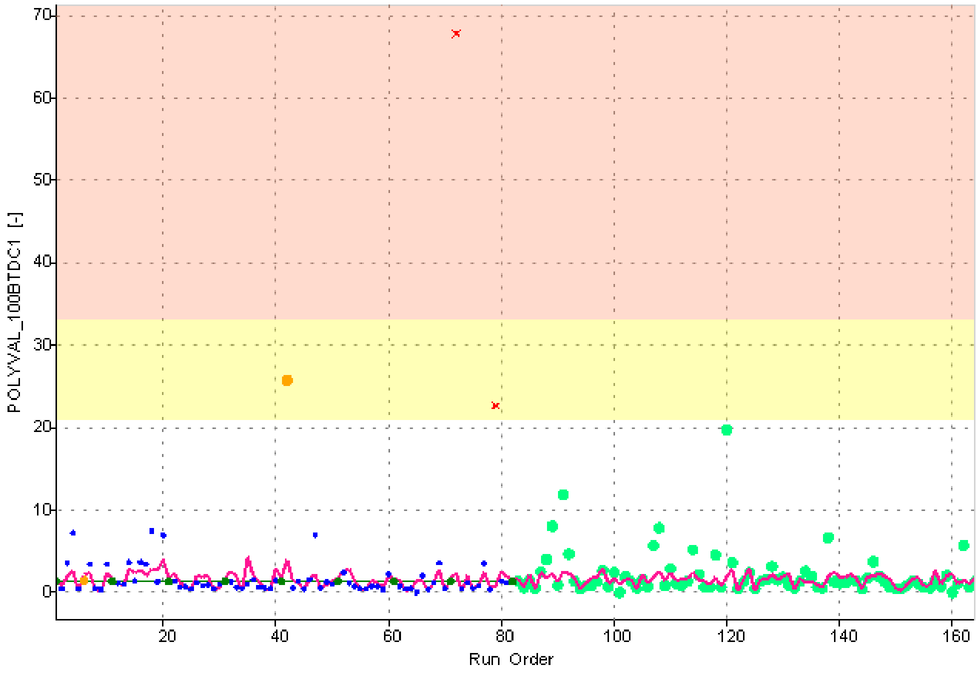


Figure 5.4: Detection of outlier, boundaries and limits are calculated automatically by the Cameo software (sigma distance from the average value)

The automation script was used to generate sample data from four sets of representative data files:

1. A gasoline engine
2. A diesel engine
3. A motored measurement
4. A loaded engine condition

This provided an initial landscape of data that would cover many of the typical measurement scenarios encountered. In each case, a SOBOL, D-Optimal and Full Factorial design was used to generate data sets. From these datasets, models were built initially using simple 2nd order polynomial designs. However, the AVL Cameo software has alternative modelling methods available (mainly Neural Network methods). In addition, the software has an automatic mode where the best model is chosen based on the data source. Figure 5.5, 5.6, 5.7 below show model quality assessment as statistics for the three different modelling approaches:

Channels

Channel: Build models Outliers Model Type: FreePolyModel

Results from modelling a Gasoline Engine – V8 5.0L

Detailed Quality Statistic

Response Name	Model Type	Positive Only	Model Quality	r2	r2adj	r2pred	Std. Model Deviation
INTHR_Slope_15BTDC1	FreePolyModel		↑	0.9998	0.99972	0.99953	0.0031683
PolyCurve_mod_Int60ATDC1	FreePolyModel		↑	0.94562	0.94127	0.93499	41.871
POLYVAL_30BTDC1	FreePolyModel		↑	0.99993	0.99992	0.9999	0.0028457
PVn135BTDC1	FreePolyModel		↑	1	1	1	9.3931e-05
PVn90BTDC1	FreePolyModel		↑	1	1	1	9.7474e-05
PVn_sub1	FreePolyModel		↑	1	1	1	5.7763e-05
POLYVAL9030BTDC1	FreePolyModel	+	↗	0.70091	0.67261	0.6356	0.42824
CG_IMEP_Error1	FreePolyModel		→	1	1	1	0.00047249
CG_IMEP_mod1	FreePolyModel		→	1	1	1	2.5174e-05
CG_PMEP_Error1	FreePolyModel		→	1	1	1	0.00047249
CG_PMEP_mod1	FreePolyModel		→	1	1	1	2.5174e-05
Error_IMEP_TDC_shift1	FreePolyModel		→	0.99941	0.99936	0.99924	0.00066942
IMEP_PCYL_TDC_mod1	FreePolyModel		→	1	1	1	4.3391e-05
INTHR_Slope_45ATDC1	FreePolyModel		→	0.99991	0.99988	0.9998	0.0036252
MBF100%1	FreePolyModel		→	0.97033	0.96517	0.95944	4.9523
MBF90%1	FreePolyModel		→	0.99622	0.99529	0.99371	1.5918
PolyCurve_mod_Int_SUB1	FreePolyModel		→	1	1	1	0.013801
PolyInt_EX1	FreePolyModel		→	1	1	1	0.017506
PolyInt_IN1	FreePolyModel		→	1	1	1	0.017161
POLYVAL1_SUB1	FreePolyModel		→	0.99973	0.99971	0.99969	0.032411
POLYVAL3090ATDC1	FreePolyModel		→	0.99989	0.99988	0.99987	0.0024739
MBF_SUB1	FreePolyModel		↘	0.89738	0.88455	0.87267	5.2319
PolyCurve_mod_Int30BTDC1	FreePolyModel	+	↘	0.92886	0.92418	0.91725	41.213
POLYVAL2_SUB1	FreePolyModel		↘	0.82459	0.81056	0.79033	0.3669
POLYVAL_100BTDC1	FreePolyModel	+	↘	0.17421	0.14245	0.079865	7.6176

Figure 5.5: Model quality and statistics for the free poly model (2nd order)

Channels

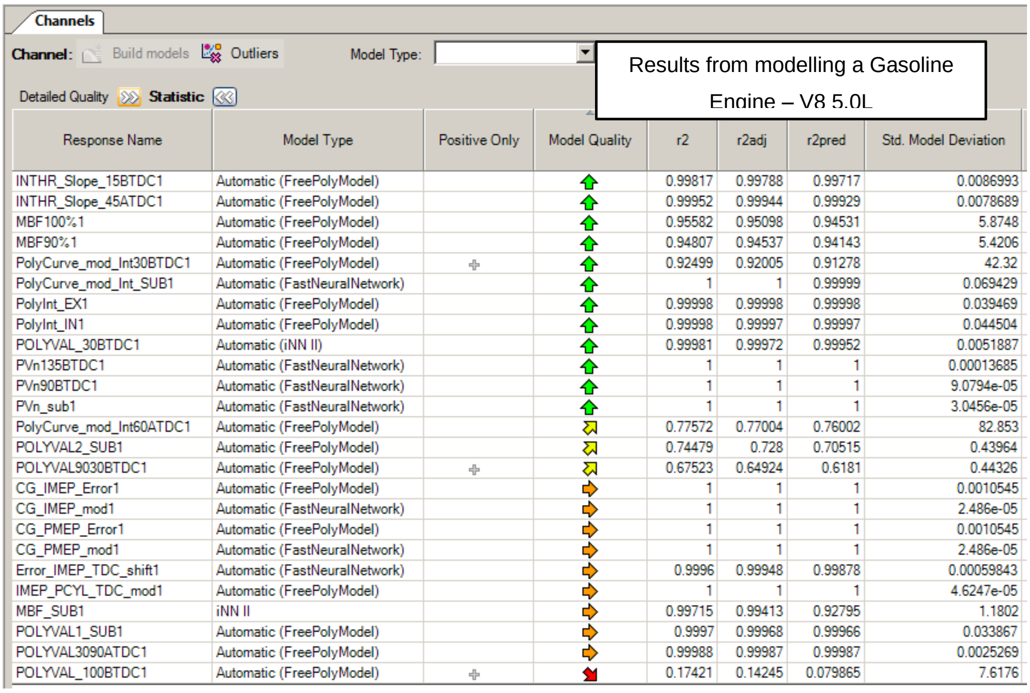
Channel: Build models Outliers Model Type: iNN II

Results from modelling a Gasoline Engine – V8 5.0L

Detailed Quality Statistic

Response Name	Model Type	Positive Only	Model Quality	r2	r2adj	r2pred	Std. Model Deviation
POLYVAL_30BTDC1	iNN II		↑	0.99981	0.99972	0.99952	0.0051887
CG_IMEP_Error1	iNN II		→	1	1	1	0.00058195
CG_IMEP_mod1	iNN II		→	1	1	1	2.1569e-05
CG_PMEP_Error1	iNN II		→	1	1	1	0.00058195
CG_PMEP_mod1	iNN II		→	1	1	1	2.1569e-05
Error_IMEP_TDC_shift1	iNN II		→	0.99927	0.99894	0.99791	0.00085775
IMEP_PCYL_TDC_mod1	iNN II		→	1	1	1	4.0109e-05
INTHR_Slope_15BTDC1	iNN II		→	0.99993	0.9999	0.99979	0.0018693
INTHR_Slope_45ATDC1	iNN II		→	0.99994	0.99992	0.99984	0.0030569
MBF100%1	iNN II		→	0.9947	0.99244	0.98572	2.3075
MBF90%1	iNN II		→	0.99992	0.99985	0.99855	0.28621
MBF_SUB1	iNN II		→	0.99715	0.99413	0.92795	1.1802
PolyCurve_mod_Int30BTDC1	iNN II	+	→	0.99878	0.99795	0.97404	6.774
PolyCurve_mod_Int60ATDC1	iNN II		→	0.99891	0.99817	0.97606	7.3885
PolyCurve_mod_Int_SUB1	iNN II		→	1	1	1	0.022119
PolyInt_EX1	iNN II		→	0.99999	0.99999	0.99998	0.032355
PolyInt_IN1	iNN II		→	1	0.99999	0.99999	0.022883
POLYVAL1_SUB1	iNN II		→	0.99968	0.99961	0.99955	0.037393
POLYVAL2_SUB1	iNN II		→	0.96741	0.9545	0.90735	0.17982
POLYVAL3090ATDC1	iNN II		→	0.9999	0.99985	0.9998	0.0027292
POLYVAL9030BTDC1	iNN II	+	→	0.98129	0.9739	0.92865	0.16058
PVn135BTDC1	iNN II		→	1	1	1	8.805e-05
PVn90BTDC1	iNN II		→	1	1	1	5.0383e-05
PVn_sub1	iNN II		→	1	1	1	2.3703e-05
POLYVAL_100BTDC1	iNN II	+	↘	0.99461	0.98944	0.36139	0.1646

Figure 5.6: Model quality and statistics for the Intelligent Neural network model



Response Name	Model Type	Positive Only	Model Quality	r2	r2adj	r2pred	Std. Model Deviation
INTHR_Slope_15BTDC1	Automatic (FreePolyModel)			0.99817	0.99788	0.99717	0.0086993
INTHR_Slope_45ATDC1	Automatic (FreePolyModel)			0.99952	0.99944	0.99929	0.0078689
MBF100%1	Automatic (FreePolyModel)			0.95582	0.95098	0.94531	5.8748
MBF90%1	Automatic (FreePolyModel)			0.94807	0.94537	0.94143	5.4206
PolyCurve_mod_Int30BTDC1	Automatic (FreePolyModel)	+		0.92499	0.92005	0.91278	42.32
PolyCurve_mod_Int_SUB1	Automatic (FastNeuralNetwork)			1	1	0.99999	0.069429
PolyInt_EX1	Automatic (FreePolyModel)			0.99998	0.99998	0.99998	0.039469
PolyInt_IN1	Automatic (FreePolyModel)			0.99998	0.99997	0.99997	0.044504
POLYVAL_30BTDC1	Automatic (iNN II)			0.99981	0.99972	0.99952	0.0051887
PVn135BTDC1	Automatic (FastNeuralNetwork)			1	1	1	0.00013685
PVn90BTDC1	Automatic (FastNeuralNetwork)			1	1	1	9.0794e-05
PVn_sub1	Automatic (FastNeuralNetwork)			1	1	1	3.0456e-05
PolyCurve_mod_Int60ATDC1	Automatic (FreePolyModel)			0.77572	0.77004	0.76002	82.853
POLYVAL2_SUB1	Automatic (FreePolyModel)			0.74479	0.728	0.70515	0.43964
POLYVAL9030BTDC1	Automatic (FreePolyModel)	+		0.67523	0.64924	0.6181	0.44326
CG_IMEP_Error1	Automatic (FreePolyModel)			1	1	1	0.0010545
CG_IMEP_mod1	Automatic (FastNeuralNetwork)			1	1	1	2.486e-05
CG_PMEP_Error1	Automatic (FreePolyModel)			1	1	1	0.0010545
CG_PMEP_mod1	Automatic (FastNeuralNetwork)			1	1	1	2.486e-05
Error_IMEP_TDC_shift1	Automatic (FastNeuralNetwork)			0.9996	0.99948	0.99878	0.00059843
IMEP_PCYL_TDC_mod1	Automatic (FreePolyModel)			1	1	1	4.6247e-05
MBF_SUB1	iNN II			0.99715	0.99413	0.92795	1.1802
POLYVAL1_SUB1	Automatic (FreePolyModel)			0.9997	0.99968	0.99966	0.033867
POLYVAL3090ATDC1	Automatic (FreePolyModel)			0.99988	0.99987	0.99987	0.0025269
POLYVAL_100BTDC1	Automatic (FreePolyModel)	+		0.17421	0.14245	0.079865	7.6176

Figure 5.7: Model quality assessment for the 'auto picked' models

The statistics shown provided an overview of the different model type quality, so that they could be compared objectively; the automatic selection mode (auto pick), provided an overall modelling landscape of the best quality for all the results when considered together. Figure 5.8 shows the model quality (using auto select mode) with respect to measured versus predicted for IMEP based results:

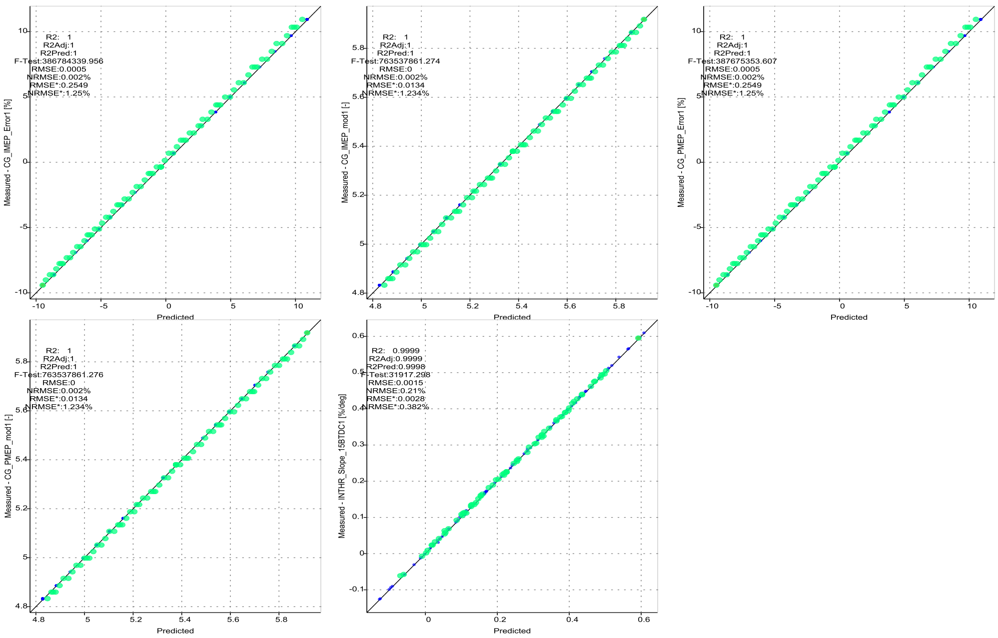


Figure 5.8: Measured vs. predicted – IMEP based results

The figures below show similar view for the other result groups, namely Heat Release (Figure 5.9), Polytropic (Figure 5.10) and PVn (Figure 5.11) based results:

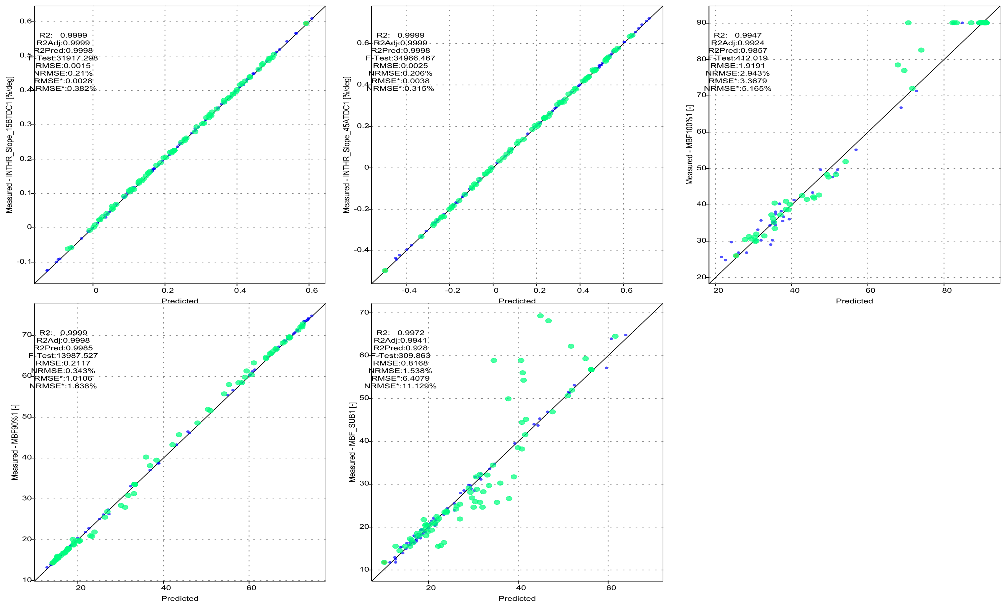


Figure 5.9: Measured vs. predicted – Heat Release derived results

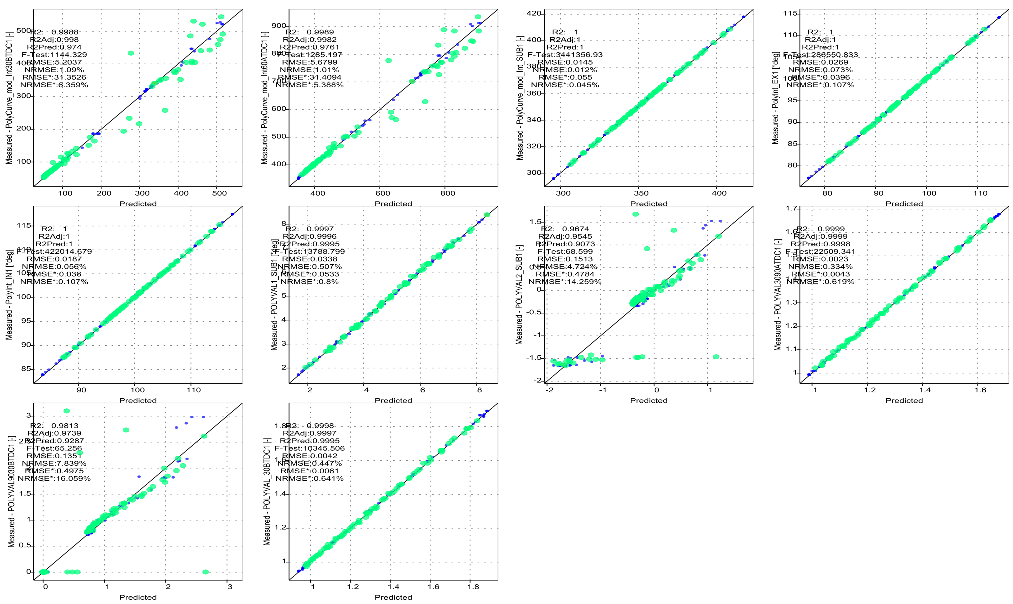


Figure 5.10: Measured vs. predicted – Polytropic derived results

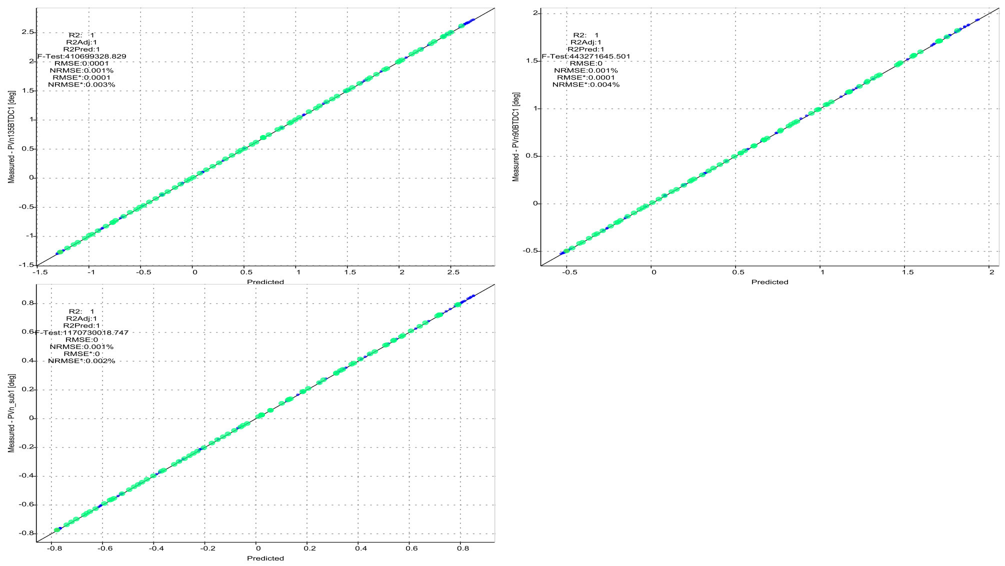


Figure 5.11: Measured vs. predicted – Process constant (PVn) derived results

In each case the blue points are training data, the green points verification data.

It was interesting to note that some of the models had an excellent fit to the training data, but when compared to the verification data (gained via a SOBOL sequence), their performance was compromised. One explanation for this phenomena could be the susceptibility of the heat release calculation to in-cylinder conditions (pressures and flows) as these factors always have inherent variability. In addition, the heat release calculations are more complex and involve more parameters than the other calculations in this study (IMEP, Polytropic, PV^n) and are therefore more sensitive to boundary conditions.

Once the modelling was completed, a detailed examination of the models could be executed. In general the R^2 predicted and Standard deviation values were used to assess model quality in an objective way. More subjectively, a visual examination of measured versus predicted could be used to append the assessment. Models were shortlisted on the basis of these performance metrics, those which did not meet minimum requirements (Std. deviation < 0.07, R2 predicted > 0.99) were deactivated. This provided a number of models which could then be examined in more with respect to response characteristics in relation to variation input. The shortlist is shown in Figure 5.12 below:

Response Name	Model Type	Model Quality	r2pred	Std. Model Deviation
PolyCurve_mod_Int_SUB1	Automatic (FastNeuralNetwork)	VeryGood	0.99999	0.069429
PolyInt_IN1	Automatic (FreePolyModel)	VeryGood	0.99997	0.044504
PolyInt_EX1	Automatic (FreePolyModel)	VeryGood	0.99998	0.039469
POLYVAL1_SUB1	Automatic (FreePolyModel)	Medium	0.99966	0.033867
INTHR_Slope_15BTDC1	Automatic (FreePolyModel)	VeryGood	0.99717	0.0086993
INTHR_Slope_45ATDC1	Automatic (FreePolyModel)	VeryGood	0.99929	0.0078689
POLYVAL_30BTDC1	Automatic (iNN II)	VeryGood	0.99952	0.0051887
POLYVAL3090ATDC1	Automatic (FreePolyModel)	Medium	0.99987	0.0025269
CG_IMEP_Error1	Automatic (FreePolyModel)	Medium	1	0.0010545
CG_PMEP_Error1	Automatic (FreePolyModel)	Medium	1	0.0010545
PVn135BTDC1	Automatic (FastNeuralNetwork)	VeryGood	1	0.00013685
PVn90BTDC1	Automatic (FastNeuralNetwork)	VeryGood	1	9.08E-05
IMEP_PCYL_TDC_mod1	Automatic (FreePolyModel)	Medium	1	4.62E-05
PVn_sub1	Automatic (FastNeuralNetwork)	VeryGood	1	3.05E-05
CG_PMEP_mod1	Automatic (FastNeuralNetwork)	Medium	1	2.49E-05
CG_IMEP_mod1	Automatic (FastNeuralNetwork)	Medium	1	2.49E-05

Figure 5.12: A table showing list of models generated from results which have appropriate quality for further usage and assessment

The models could then be classified and grouped according to the type of curve from which they were derived; this is shown in Figure 5.13:

Response Name	Model Type	Model Quality	r2pred	Std. Model Deviation	Result type
CG_IMEP_Error1	Automatic (FreePolyModel)	Medium	1	0.0010545	IMEP
CG_PMEP_Error1	Automatic (FreePolyModel)	Medium	1	0.0010545	IMEP
IMEP_PCYL_TDC_mod1	Automatic (FreePolyModel)	Medium	1	4.62E-05	IMEP
CG_PMEP_mod1	Automatic (FastNeuralNetwork)	Medium	1	2.49E-05	IMEP
CG_IMEP_mod1	Automatic (FastNeuralNetwork)	Medium	1	2.49E-05	IMEP
PolyCurve_mod_Int_SUB1	Automatic (FastNeuralNetwork)	VeryGood	0.99999	0.069429	POLY
PolyInt_IN1	Automatic (FreePolyModel)	VeryGood	0.99997	0.044504	POLY
PolyInt_EX1	Automatic (FreePolyModel)	VeryGood	0.99998	0.039469	POLY
POLYVAL1_SUB1	Automatic (FreePolyModel)	Medium	0.99966	0.033867	POLY
POLYVAL_30BTDC1	Automatic (iNN II)	VeryGood	0.99952	0.0051887	POLY
POLYVAL3090ATDC1	Automatic (FreePolyModel)	Medium	0.99987	0.0025269	POLY
PVn135BTDC1	Automatic (FastNeuralNetwork)	VeryGood	1	0.00013685	PVN
PVn90BTDC1	Automatic (FastNeuralNetwork)	VeryGood	1	9.08E-05	PVN
PVn_sub1	Automatic (FastNeuralNetwork)	VeryGood	1	3.05E-05	PVN
INTHR_Slope_15BTDC1	Automatic (FreePolyModel)	VeryGood	0.99717	0.0086993	ROHR
INTHR_Slope_45ATDC1	Automatic (FreePolyModel)	VeryGood	0.99929	0.0078689	ROHR

Figure 5.13: A table showing models classified according to curve from which they were derived

The models could then be visualised in order to make an assessment of which results had some appropriate response relative to variation stimulation. These were plotted as a model intersection plot, Figure 5.14 shows the variation of IMEP based results compared to the variation inputs:

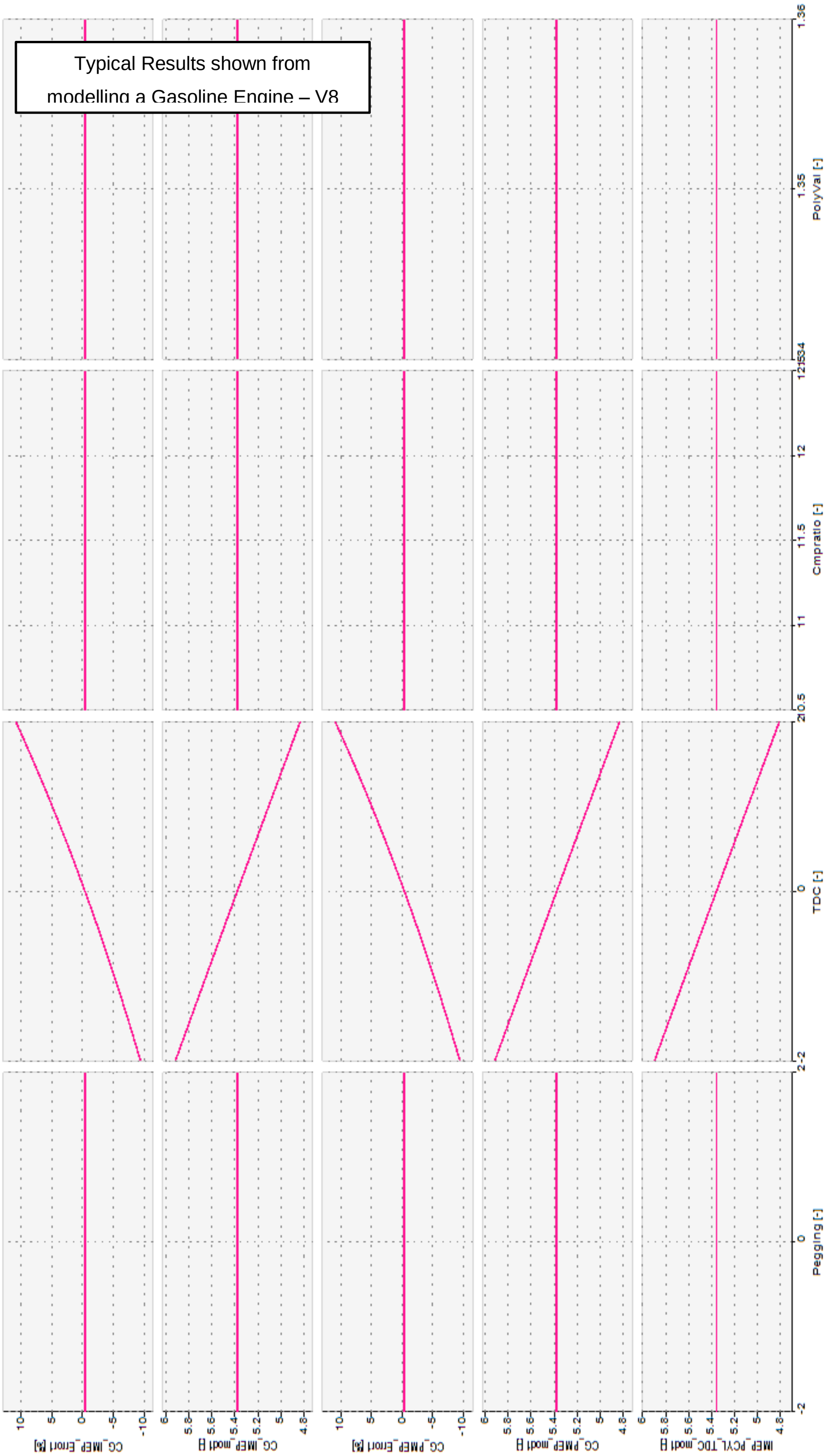


Figure 5.14: IMEP results variation vs. response intersection plot

The IMEP based results show significant response with respect to TDC variation, but almost no response to the other stimuli. It is well established that IMEP is very sensitive to TDC related errors! A surprising observation was the lack of response with respect to changes in compression ratio. In the literature, it was suggest that error in IMEP is proportional to the compression ratio error – but for a motoring cycle only [24]. One explanation could be the fact that compression ratio itself is not called directly in the IMEP calculation, so variation of the value only has a very slight, indirect effect via the volume table.

The heat release result in Figure 5.15 below showed some sensitivity to all input variation, but the most extremes response was seen to be in relation to pegging error variation. It is expected that, as the heat release calculations taken into account volume and process definition, that there would be some response to all for input variations.

Figure 5.15: ROHR results variation vs. response intersection plot

The Polytropic results shown in Figure 5.16 below demonstrate some level of sensitivity to both Pegging and TDC variations, this can be validated as correct due to the fact that the Polytropic curve is derived directly from the pressure and volume relationship and nothing else - hence compression volume and polytropic setting in the parameters have no impact.

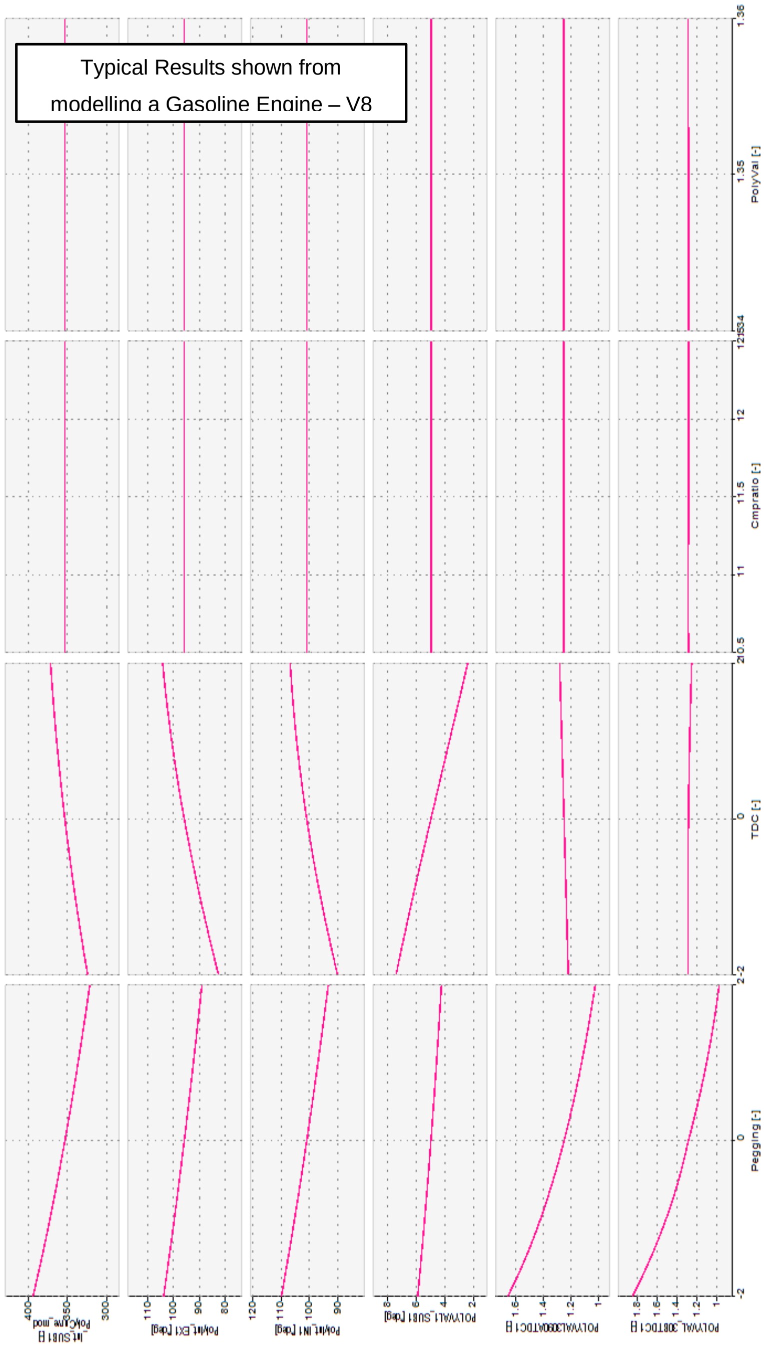


Figure 5.16: POLY results variation vs. response intersection plot

The Process constant results (Figure 5.17) are also derived from the pressure and volume relationship and thus have some sensitivity to all input variation. However, the impact of pegging variation is very significant when compared to the others, so much so that it can stated that the level of sensitivity of these results when stimulated by other inputs (than pegging) can effectively be ignored as they are practically insignificant by comparison.

Figure 5.17: PVn results variation vs. response intersection plot

5.3 Data validation with verification measurements

In order to be able to develop a high confidence level in the model created from the simulation environment. A comparison was carried out with real, measured data samples, compared to the data with induced errors from the simulation environment. The process of collecting this 'real error' data, and ensuring data consistency is described in Chapter 4. This data was firstly analysed itself for quality and then compared directly to error data generated by the simulation environment to qualify the behaviour of the simulated errors compared to data with real errors of the same type and magnitude.

As discussed and described in chapter 4.11, measurements were taken with actual errors induced (according to the measurement plan – on specific a defined target engine – a V8 5.0l Gasoline engine). Errors were induced at the extreme limit points, plus zero error, plus a verification measurement at zero error after the specific measurement procedure. Using the TDC error as an example – a measurement was taken with the encoder setting parameter with a plus and minus two degree error, at each operating condition, this gave three sets of measurement data at each different operating condition.

Where possible, the errors were induced in the software parameters. This is preferable to physically applying errors as there are fewer disturbances to the test subject and test system, so there is less chance that unintentional errors are induced due to physically disturbed components.

5.3.1 TDC based errors

Initial analysis of the data files showed good correlation between simulated and real errors. Figure 5.18 shows verification of the simulation data as follows – four curves are shown on the screen, the real measured curve (average curve from 100 cycles – PCYL_AVG4 coloured pink) with no error, this is overlaid to a simulated curve of the same data, with no error induced (hence perfectly overlaid – PCYL_MOD4 coloured red). On the same scales, the curve showing physically induced errors are shown (PCYL_AVG4 coloured salmon and green). These latter curves show the effect of the induced error of plus and minus two degrees crank angle. This diagram can be taken as baseline data.

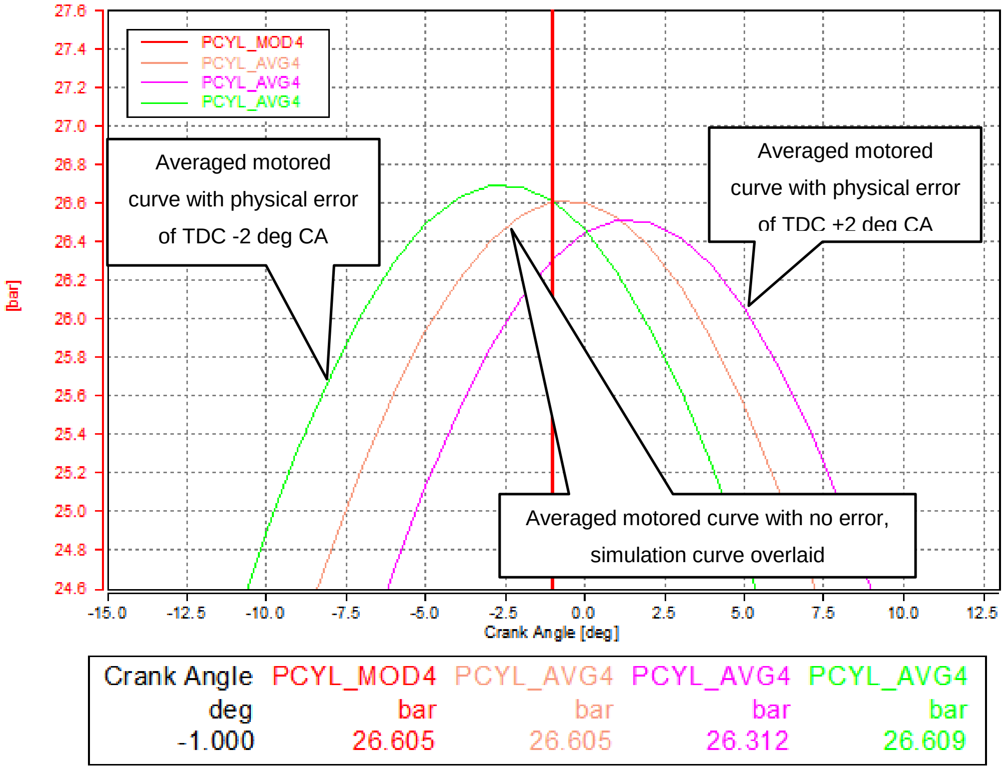
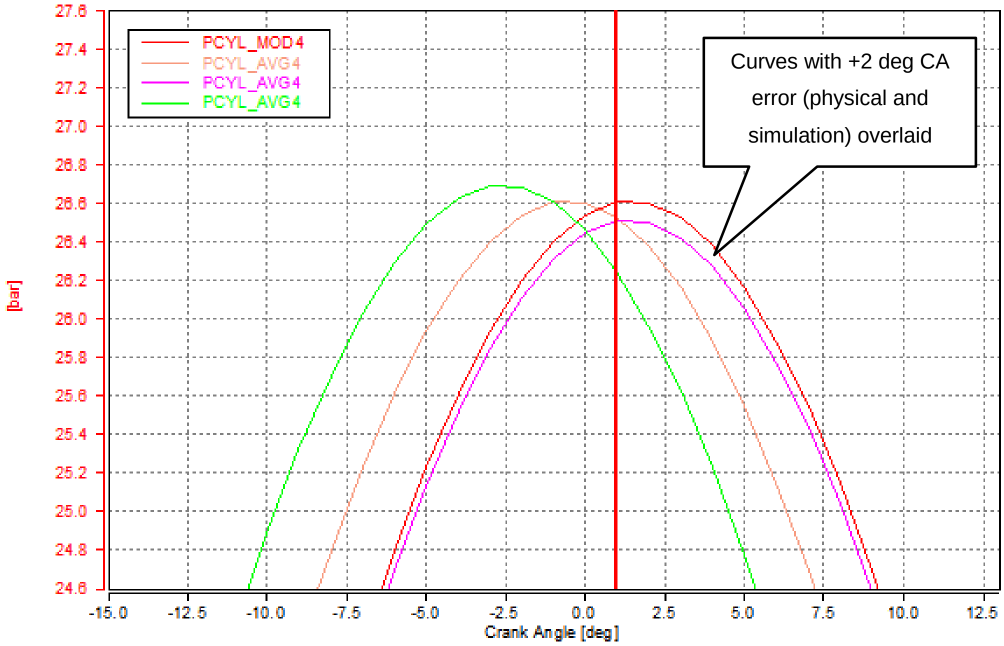


Figure 5.18: TDC Error baseline data

The diagram below (Figure 5.19) shows the effect of an error, introduced in simulation. Here it can be clearly seen that as an error of plus two degrees on the TDC parameter is induced, the red curve PCY_MOD4 moves to a position where it overlays perfectly over the measured curve with the actual error applied during the measurement.

A similar effect can be seen with a TDC error induced in simulation in the opposite direction (minus two degrees) – Figure 5.20. The curves overlay perfectly from real error data, and simulated error data. Note that in these cases, motored data has been used as this is free from the usual cycle-to-cycle variation normally seen in a gasoline engine when combustion is occurring.



Crank Angle	PCYL_MOD4	PCYL_AVG4	PCYL_AVG4	PCYL_AVG4
deg	bar	bar	bar	bar
1.000	26.605	26.525	26.508	26.248

Figure 5.19: Averaged, motored curve with error generated by simulation, compared to a curve with a physical error (plus 2 degrees crank angle) – note near perfect overlay of PCYL_MOD4 over PCYL_AVG4 coloured pink)

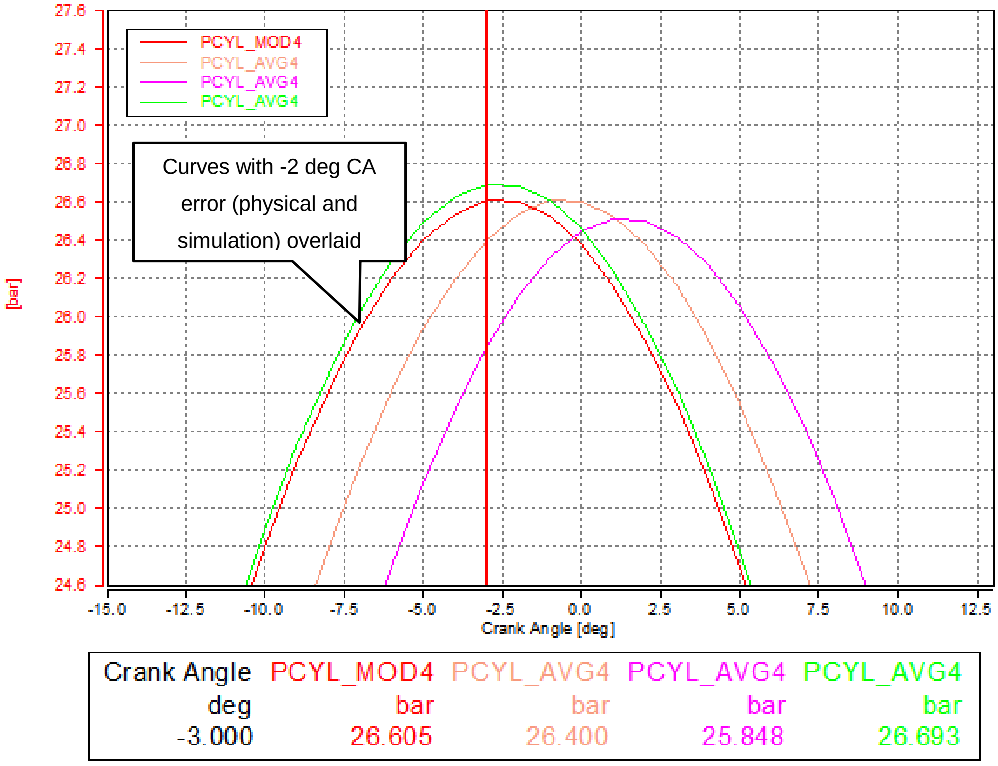


Figure 5.20: Curve is now shifted in opposite direction and compared to a curve with a physical error (minus 2 degrees crank angle) – note again the near perfect overlay of PCYL_MOD4 over PCYL_AVG4 coloured green)

In summary, the correlation for motored data was excellent and better than expected. It was also necessary however to compare the performance of the simulated errors with real errors with respect to fired data, where combustion introduces some aspect of instability into the real measured data that has errors induced. Averaged curves were again used for comparison. The data was also examined for stability using the coefficient of variance of IMEP from each measurement as a quality metric for this factor.

In Figure 5.21 below, the averaged pressure curves from cylinder number four, under fired, loaded conditions are shown overlaid. The pink/red curve is the curve with no error (raw data and simulation data overlay perfectly as expected), the green curve shows the effect of a plus two degree and the salmon coloured curve, a minus two degree error on the TDC position. This can be considered a reference measurement data set.

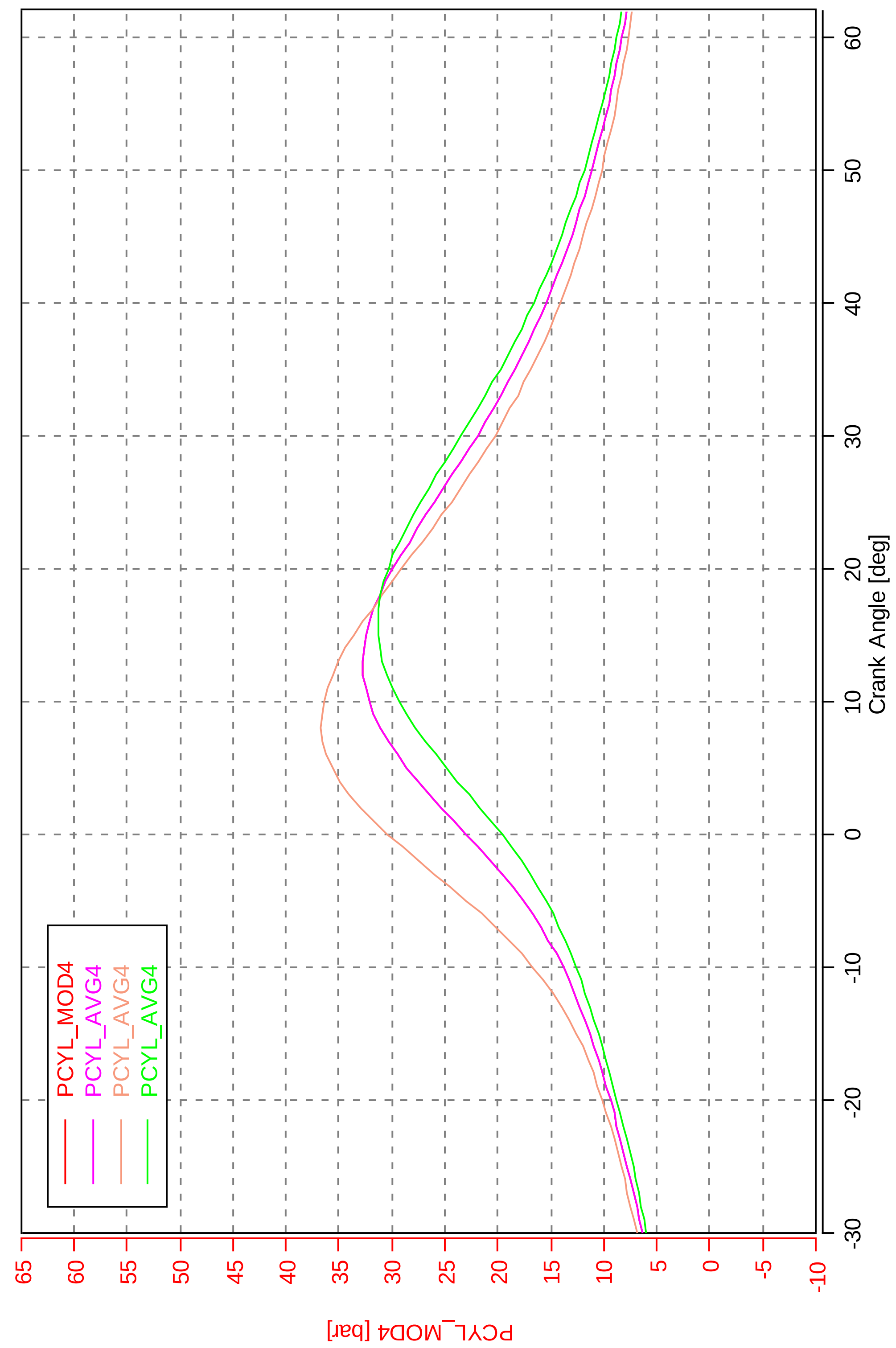


Figure 5.21: Cylinder 4 average curves (of 300 cycles), showing no error, and plus/minus 2 degrees error on TDC position

Figure 5.22 now shows the effect of inducing an error in simulation on TDC, in this case, a plus two degree error was applied to the simulation data (red curve). Now it can clearly be seen that the curve offset has the correct orientation, also, the difference in IMEP between measured and calculated data can be noted, which in this case, is approximately 0.5%. This is excellent correlation of the values when it is considered that there are different measurement data sets (taken separately) being used.

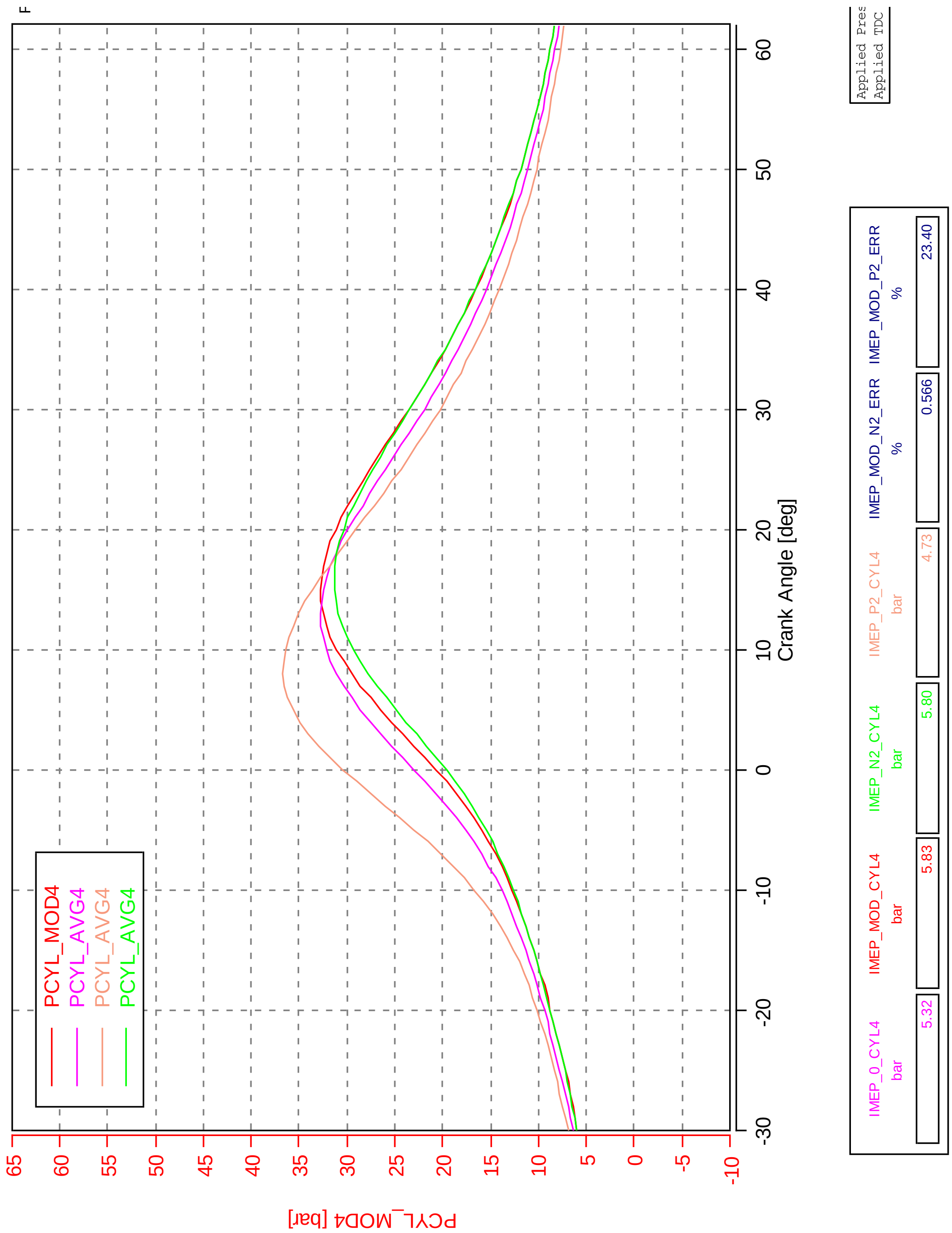


Figure 5.22: The effect of inducing an error in simulation on TDC

For further correlation, consider Figure 5.23 below. This is the opposite extreme compared to the above. The IMEP error is higher but still within acceptable limits. In summary, the data shows that at this point, it can be suggested with confidence, that the simulation induced errors, align very well with the physically induced TDC errors.

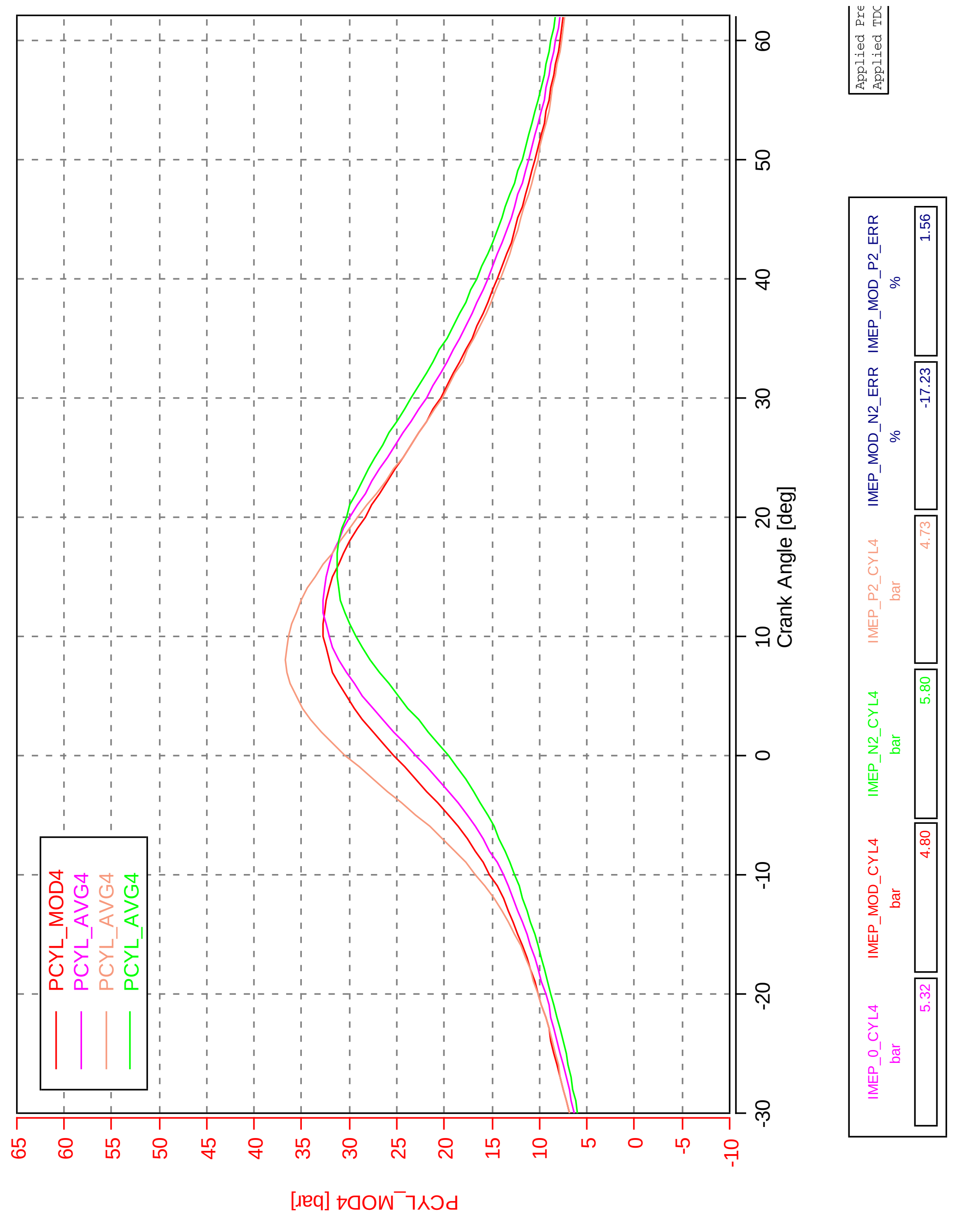


Figure 5.23: Opposite extreme compared to the above in Fig 5.22

5.3.2 Pressure scale errors

In order to further gain confidence in the simulation environment, it was decided to execute a similar evaluation to the above, with respect to the zero level/pegging shifts. A test sequence was executed as described in Chapter 5 and this provided measurement for the basis of comparison. As before, all measured curves were taken at steady state operating conditions, and then averaged to produce a single, representative pressure curve for that single measurement point. Data was measured with zero error, then plus/minus the extreme limits, then verification of zero error conditions (post-test). Figure 5.24 below shows data from the initial conditions with zero error applied.

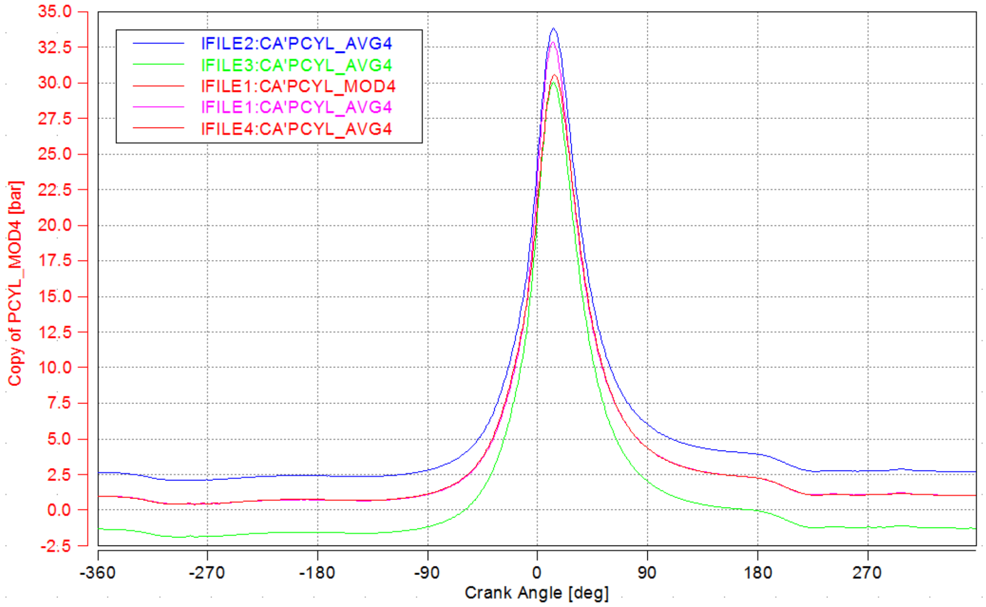


Figure 5.24: Initial status, no pegging error applied, simulation and real data are overlaid fully

Firstly, a plus two bar offset to the simulated curve was applied, this was then compared to the curve with the actual plus two bar error created during the measurement. Figure 5.25 shows the curves in the same diagram on the same axis:

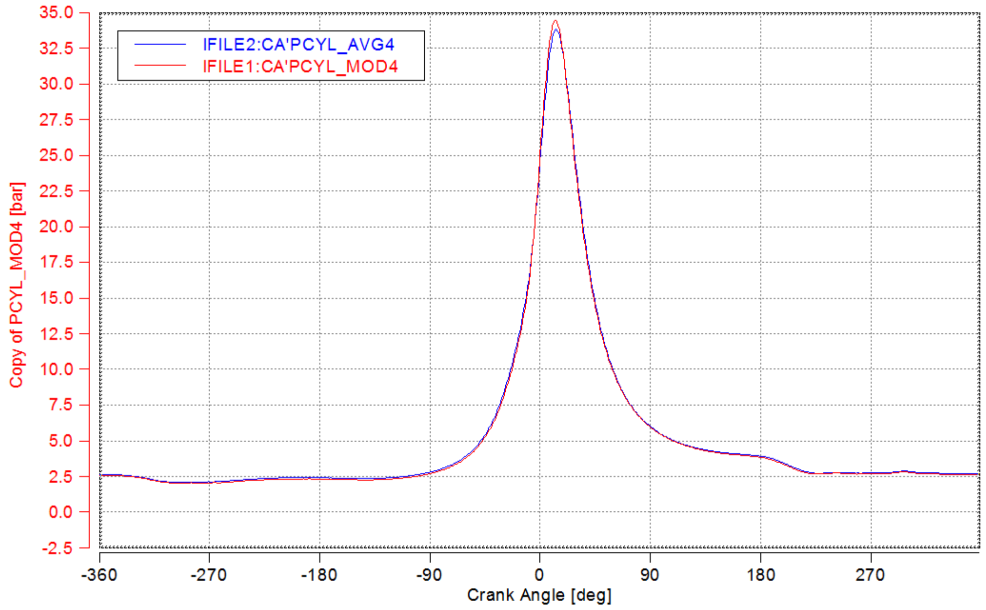


Figure 5.25: Simulation and Real curves with plus 2 bar error

As previously, the opposite was applied and the curves were compared with minus two bar error (Figure 5.26)

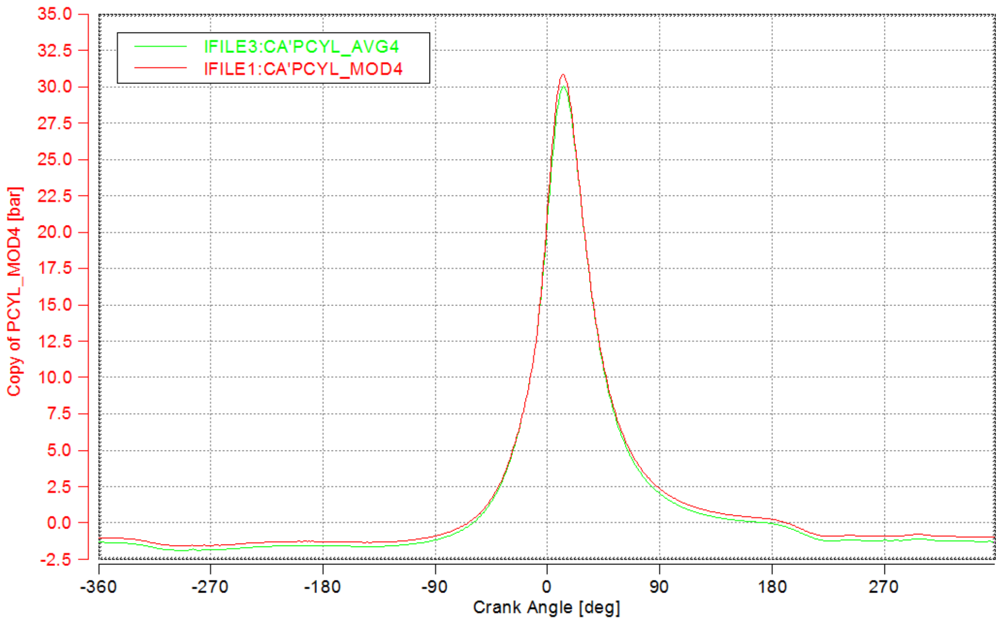


Figure 5.26: Measured and simulated curves with minus 2 bar error on pressure scale (Y axis)

As can clearly been seen in the diagrams, the averaged curves generated by the simulation environment, with the induced errors, correlate very well with actual measured data which has the errors intentionally induced with respect to TDC errors, and zero level/pegging errors.

5.3.3 Polytropic based errors

The scaling and TDC based errors are similar in that they both affect the positioning of the pressure curve relative to its axes – they are therefore 'dynamic' errors in their nature and they have a similar effect on the raw data. However, the polytropic based errors are 'static' errors and they do not directly affect the measured curves of pressure and volume during measurement run time. The reason is that the polytropic parameter is only used in conjunction with certain indirect calculations as it defines the thermodynamic process between two states of pressure and volume, during a compression or expansion. Therefore with respect to acquiring the raw data, it will have no effect on the accuracy of the acquired data when set incorrectly. The only exception being, those calculations that use the polytropic coefficient, that are being executed <u>during</u> measurement run time. For data processing after the measurement there is no impact. However, there is an exception to this, depending on the set-up of the measurement device, in particular, with respect to zero level correction (pressure scale correction and adaption on a cyclic basic, necessary due to the relative pressure signal provided by piezo-electric based pressure sensors that are almost exclusively used in this application), which on most commercial measurement systems, is executed during run time. The reason is that many systems support the 'thermodynamic' method of offset correction – this method uses the difference in pressure (provided by the sensor) between two volume states, in conjunction with the polytropic coefficient to calculate the absolute pressure at the initial volume state. This value is then used to correct and adjust the whole pressure curve for that cycle. The calculation is discussed in Chapter 3.

Therefore, it should be noted that, if this method of zero level correction is employed, then, this <u>will</u> have a direct impact on the raw measured data (the pressure scale offset). However, this error would manifest itself as a pressure scale error, and thus, would be captured as such. So even if the error was not identified specifically (i.e. as a polytropic error), it would be captured within the suggested 80% group of main errors within the scope of this work, so from a condition monitoring viewpoint – this error state can be overlooked.

In order to be consistent, it was decided to compare the simulation data with real, measured data that contained the polytropic error. In order to compare again the quality of simulation with real measured error data - as polytropic errors have no real effect on the raw data curves - it was decided to use heat release curves as a basis for the comparison, as these algorithms definitely use the polytropic parameter and would definitely show differences very clearly. In order to execute this, a simple calculation model, using existing macro functions, in conjunction with those developed within the scope of this work, was developed within AVL Concerto and used. These calculations were executed within the 'graphical' programming environment available within the AVL Concerto and Indicom software tools. The model used is shown in Figure 5.27 below:

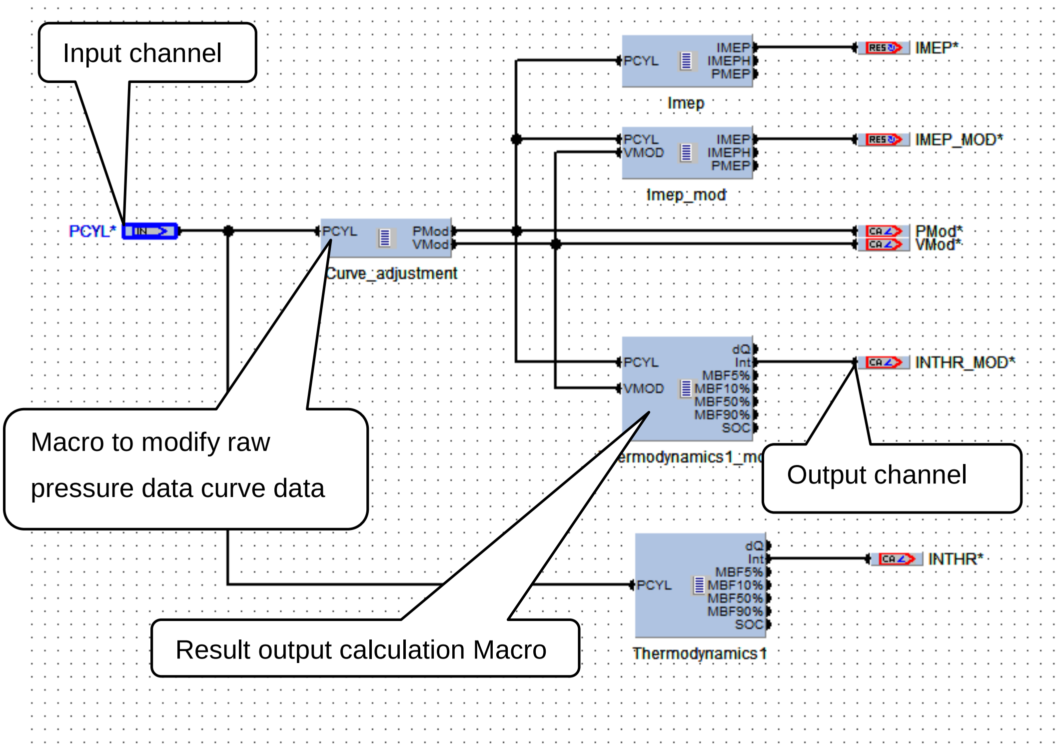


Figure 5.27: Heat release calculation model used to verify simulation and measured data with respect to Polytropic errors – showing model based formula compiler - CalcGraf

The model uses a target data file as input; this is an averaged pressure curve from a measurement procedure. The curve is adjusted according to the simulation to apply the pressure and volume offset errors. This creates an error induced version of the original pressure and volume curves (PMod and Vmod). The heat release is then calculated using standard, simple algorithms (based on Rassweiler and Withrow [33]). Note that one of the macros has a separate volume input, also that both macros use different values for the polytropic parameter, one uses an unmodified value, the other used a modified value from the measurement data with the error applied. This provided 3 curves for comparison:

- One unmodified, derived from the standard curve
- One modified according to simulation environment
- One unmodified, from measurement, with a polytropic error defined during measurement

This allows direct comparison of unmodified data, data with errors induced by simulation, and data with errors induced during measurement. The curves are shown below in Figure 5.28. In this case the data is motored:

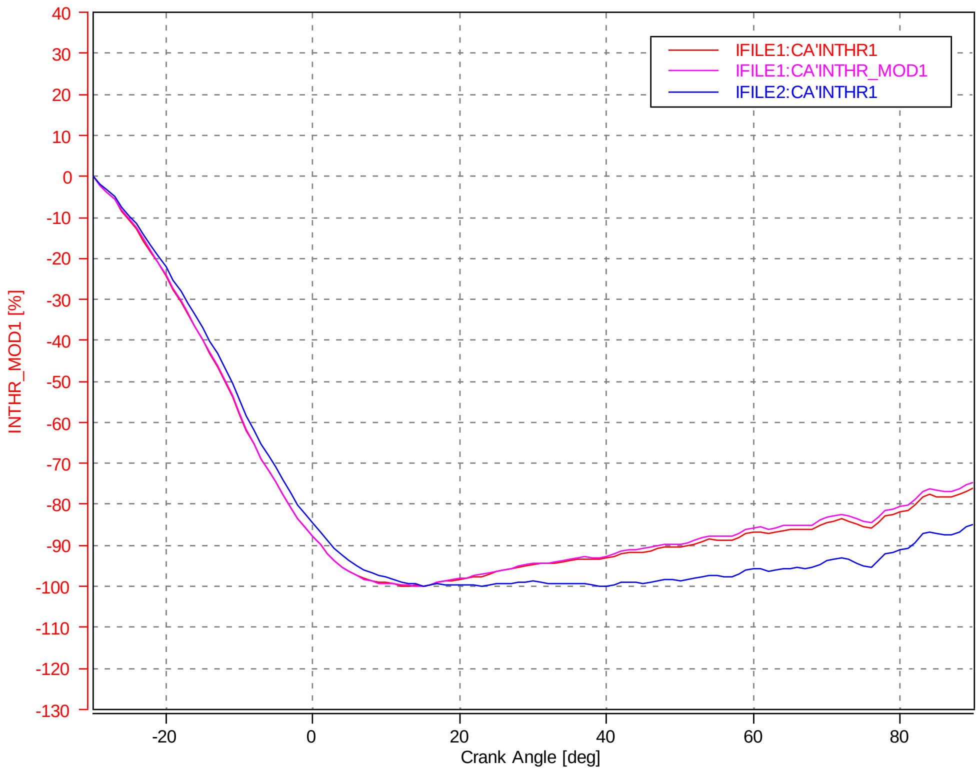


Figure 5.28: Integrated heat curves, derived from motored data

With respect to Figure 5.28 - the pink and red curves show raw data and simulation data (with no error applied). The blue curve is the measured data with the error of -0.01 applied to the polytropic coefficient.

Fig 5.29 below shows that same data, with the same error offset applied in the measured and simulated data. It can be clearly seen that there is good correlation between measurement and simulation with the same error. Figure 5.30 shows similar correlation with errors applied of the same magnitude but opposite polarity (+0.01).

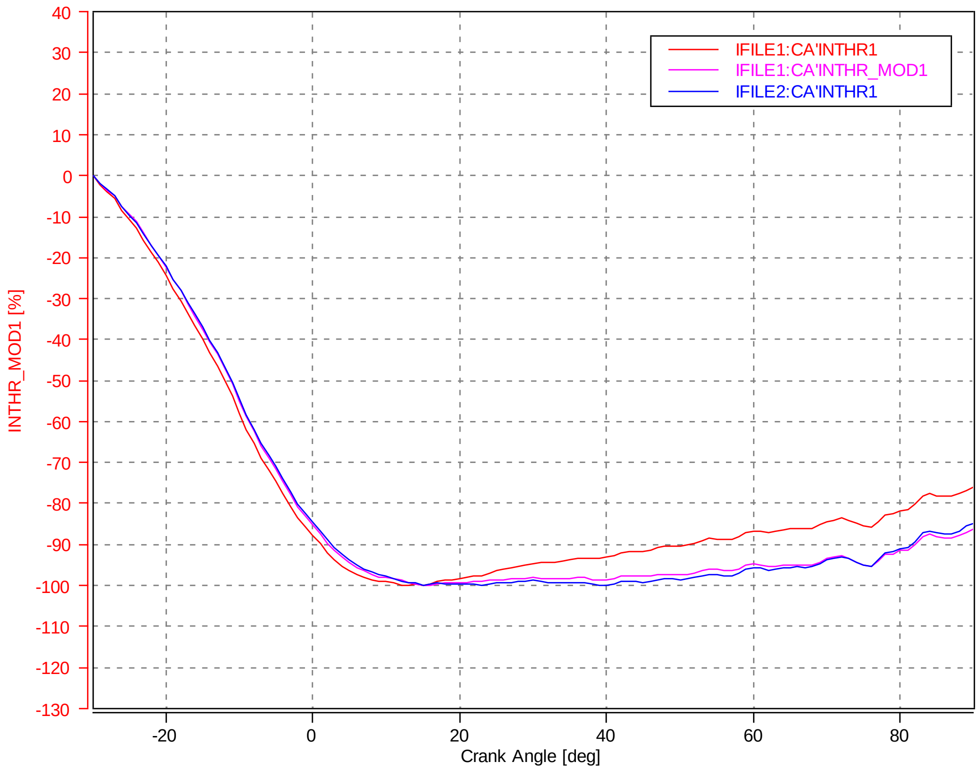


Figure 5.29: Integrated heat curves, derived from motored data, with -0.01 error applied in simulation

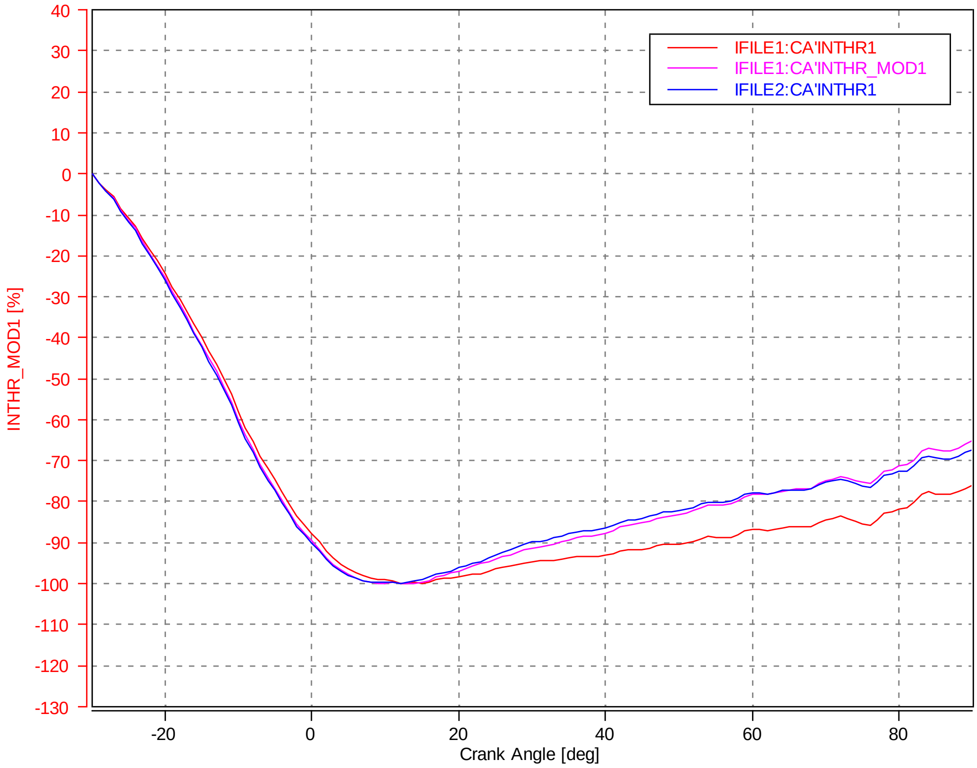


Figure 5.30: errors applied of the same magnitude but opposite polarity (+0.01)

This level of correlation was also seen of the loaded data. A comparison is shown below in Figure 5.31:

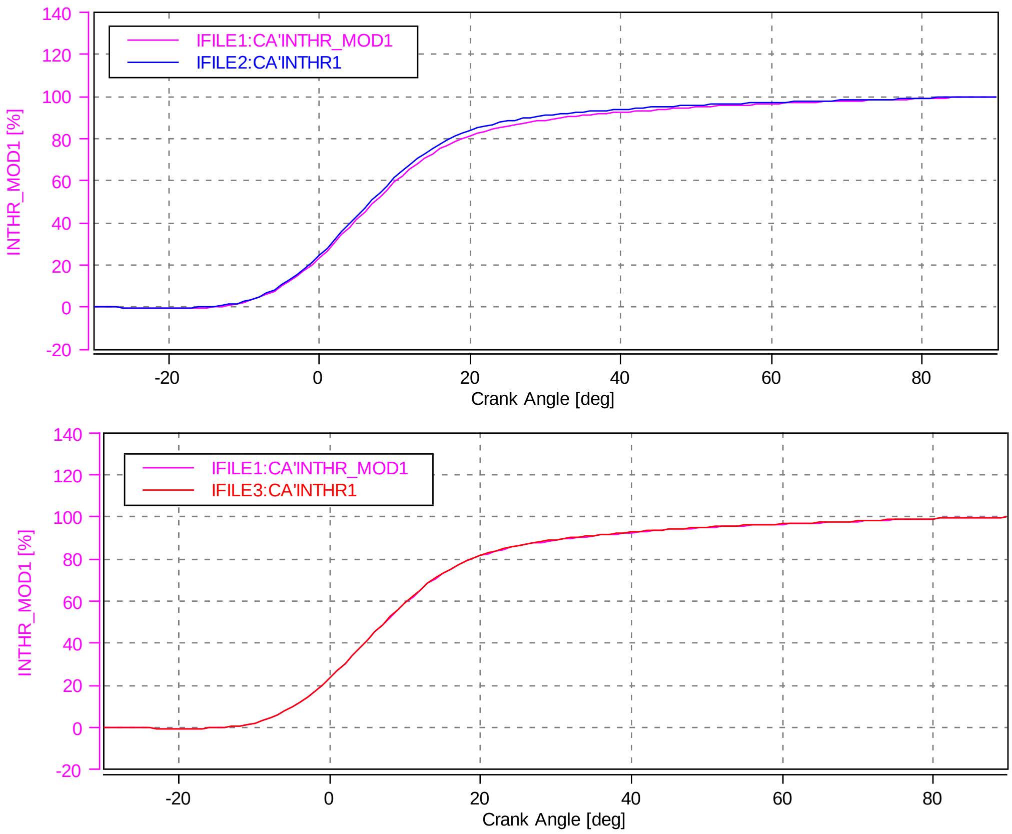


Figure 5.31: Loaded engine operating condition

IFile 2 is the heat curve derived from measured data with a -0.01 offset applied to the data during measurement. IFile 3 is the same but with the error applied of opposite polarity. In this case IFile1 has an error applied (in simulation) to the polytropic value, of +0.01, and this correlates perfectly with IFile3. The opposite condition and correlation is shown in Figure 5.32 below.

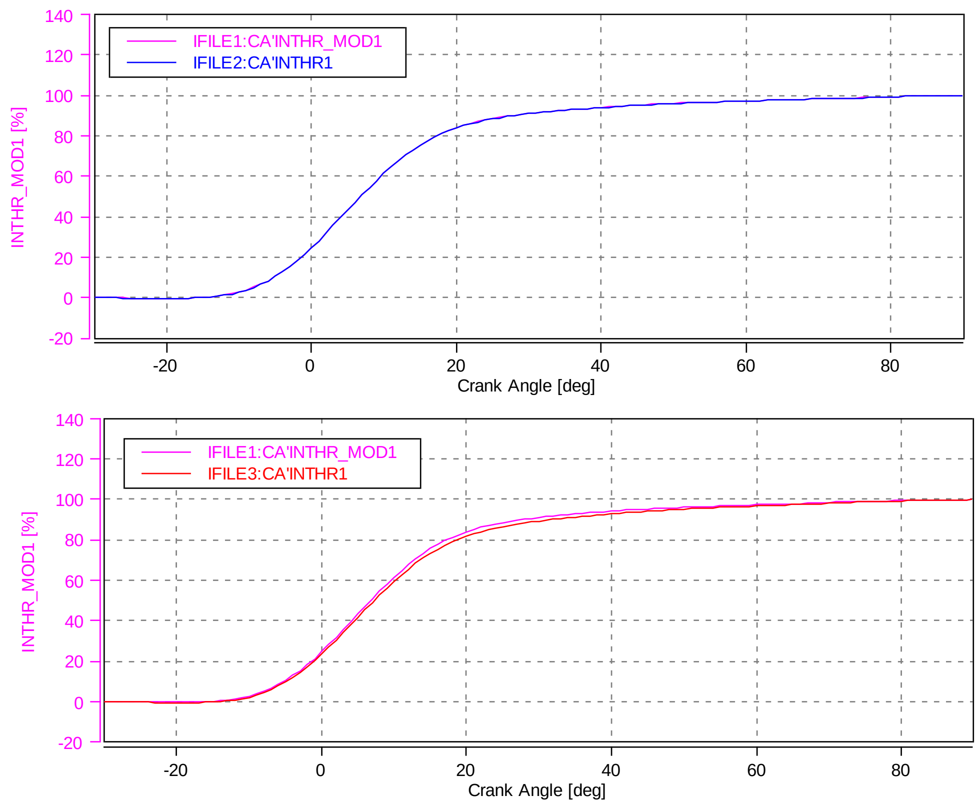


Figure 5.32: Loaded engine operating condition - IFile1 has an error applied (in simulation) to the polytropic value, of -0.01, and this correlates perfectly with IFile2 that had the same error applied during measurement

5.3.4 Compression ratio definition errors

As a final step, it was necessary to correlate measurement and simulation with respect to Compression ratio errors. A similar approach and technique to the above evaluations was used. In this case again though, it is worthy to note the effect of a wrongly defined compression ratio. In common with the polytropic error, the compression ratio error can be considered a 'static' error – it does not have a direct effect on the measured pressure curve or its relative positioning on the axis of pressure of volume (crank-angle). However, the effect can be seen clearly on the volume curve in Figure 5.33 and 5.34 below. The red curve is the difference between the two curves in percent.

The actual volume and error volume curves (error from simulation) are overlaid on the same axis.

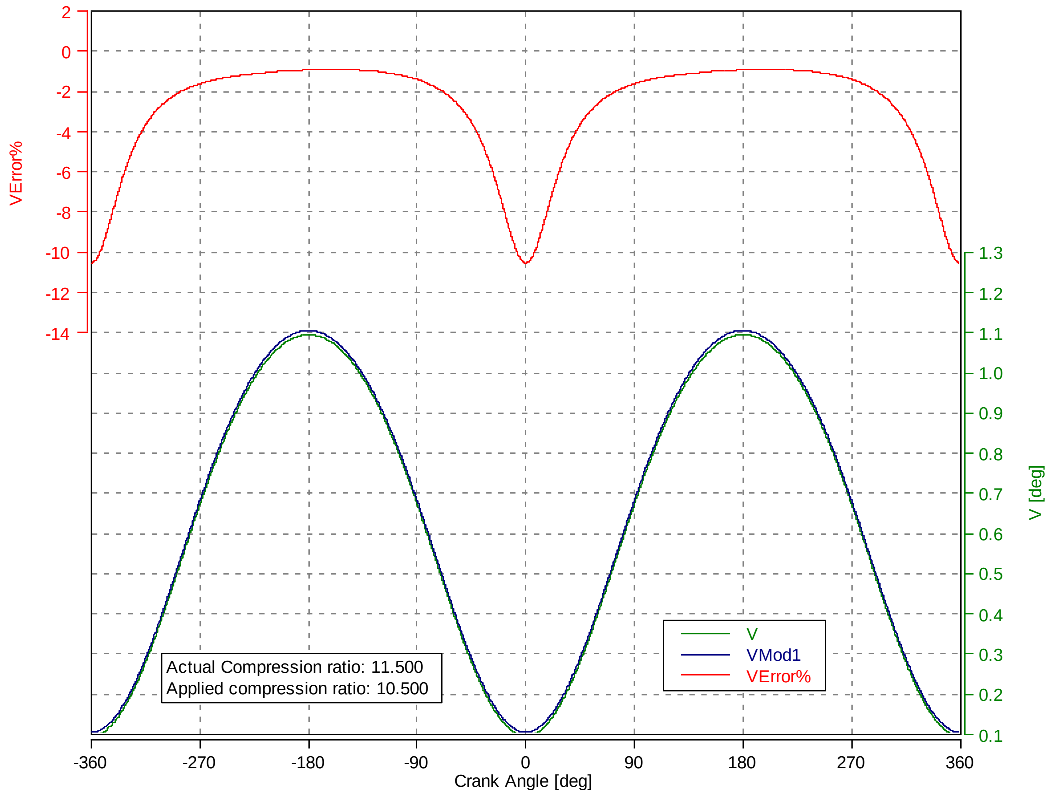


Figure 5.33; The effect of incorrect compression ratio definition on the volume curve, in this diagram, an error of -1 ratio of compression is applied

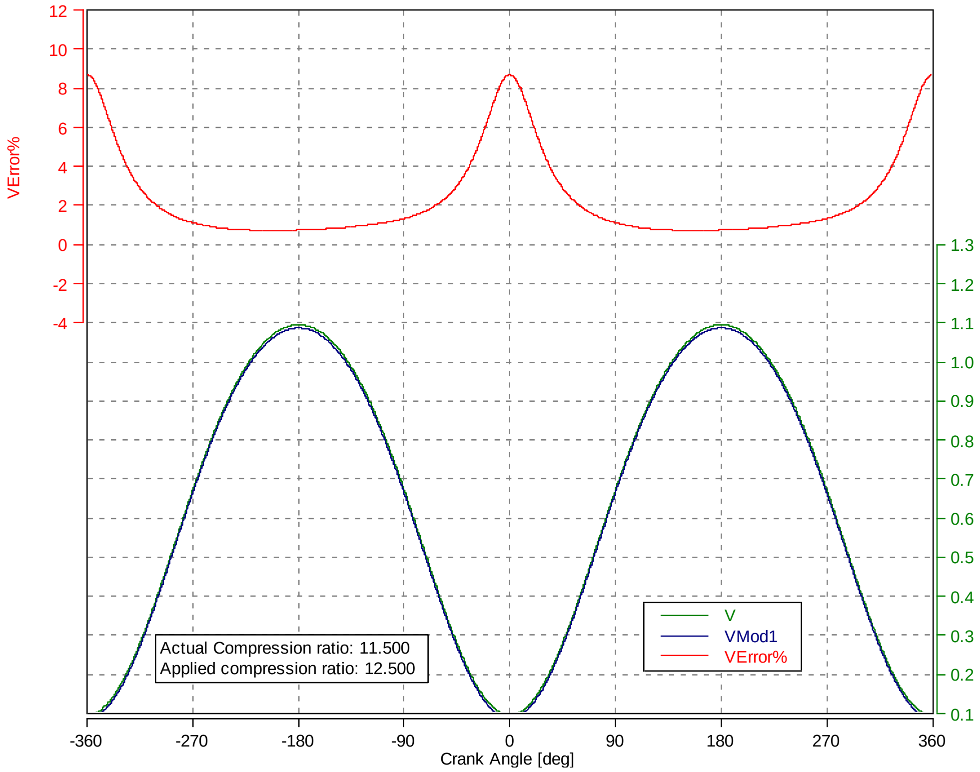


Figure 5.34: Incorrect compression ratio of +1 applied to volume curve in simulation

For comparison, the raw data/simulation data was compared with data from measurements with the errors applied (+/- one ratio of compression). Figure 5.35 below shows the volume curves, and the volume difference (%) curves overlaid. Also, on the right hand side the curves are zoomed for more detail. The initial situation is shown with no errors applied to the simulation data. The pink and red curves show the general effect of the plus/minus one ROC (Ratio of Compression).

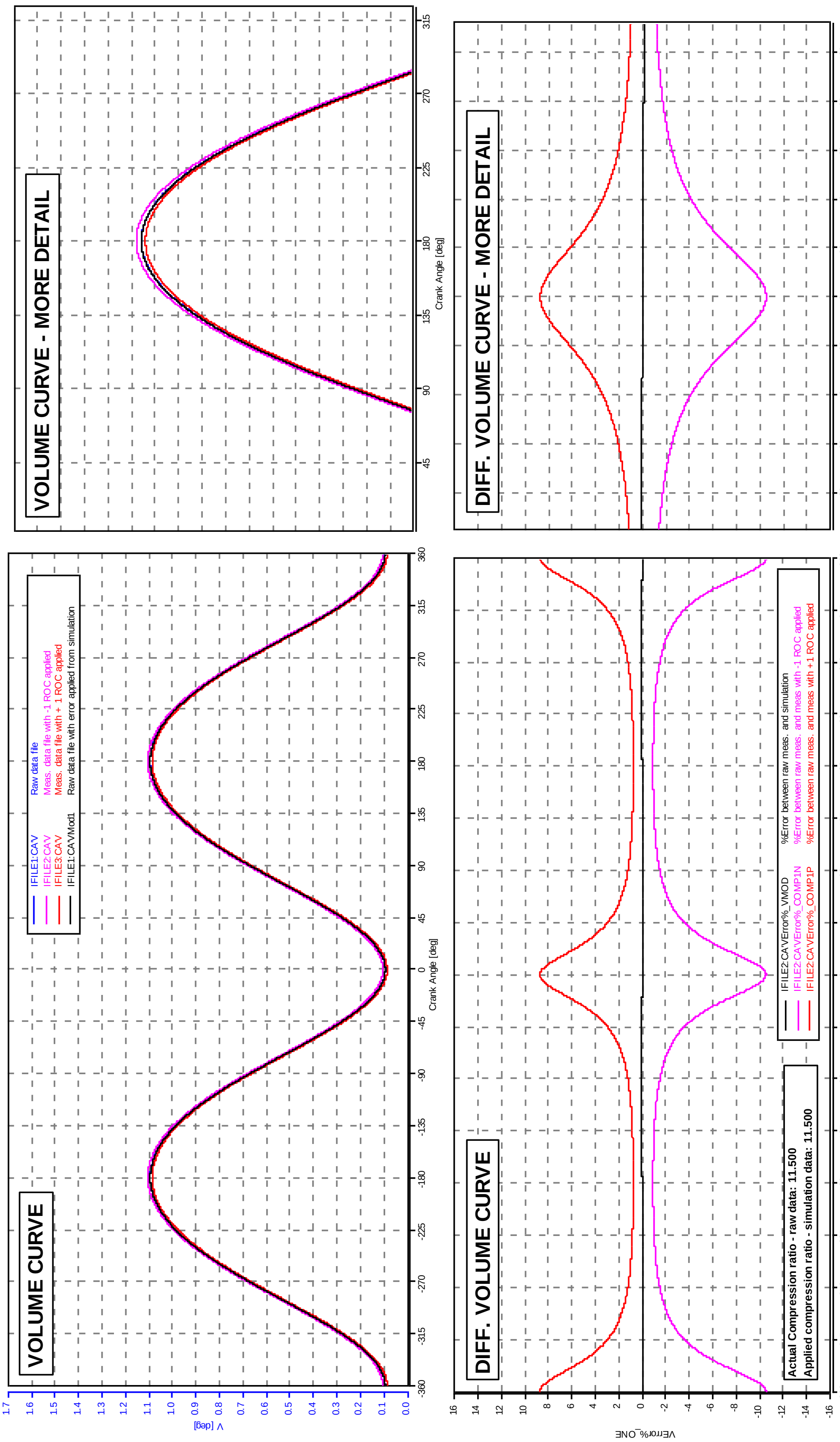


Figure 5.35: Volume curves, and difference volume curves from raw data, simulation data with no errors, and measurement data with negative and positive error of 1 ratio of compression (ROC) applied

The same plot is now used below in Figure 5.36 and Figure 5.37, with the errors (plus and minus 1 ROC) applied in simulation. It can be seen that there is good correlation between simulation data, and data with errors applied during measurement.

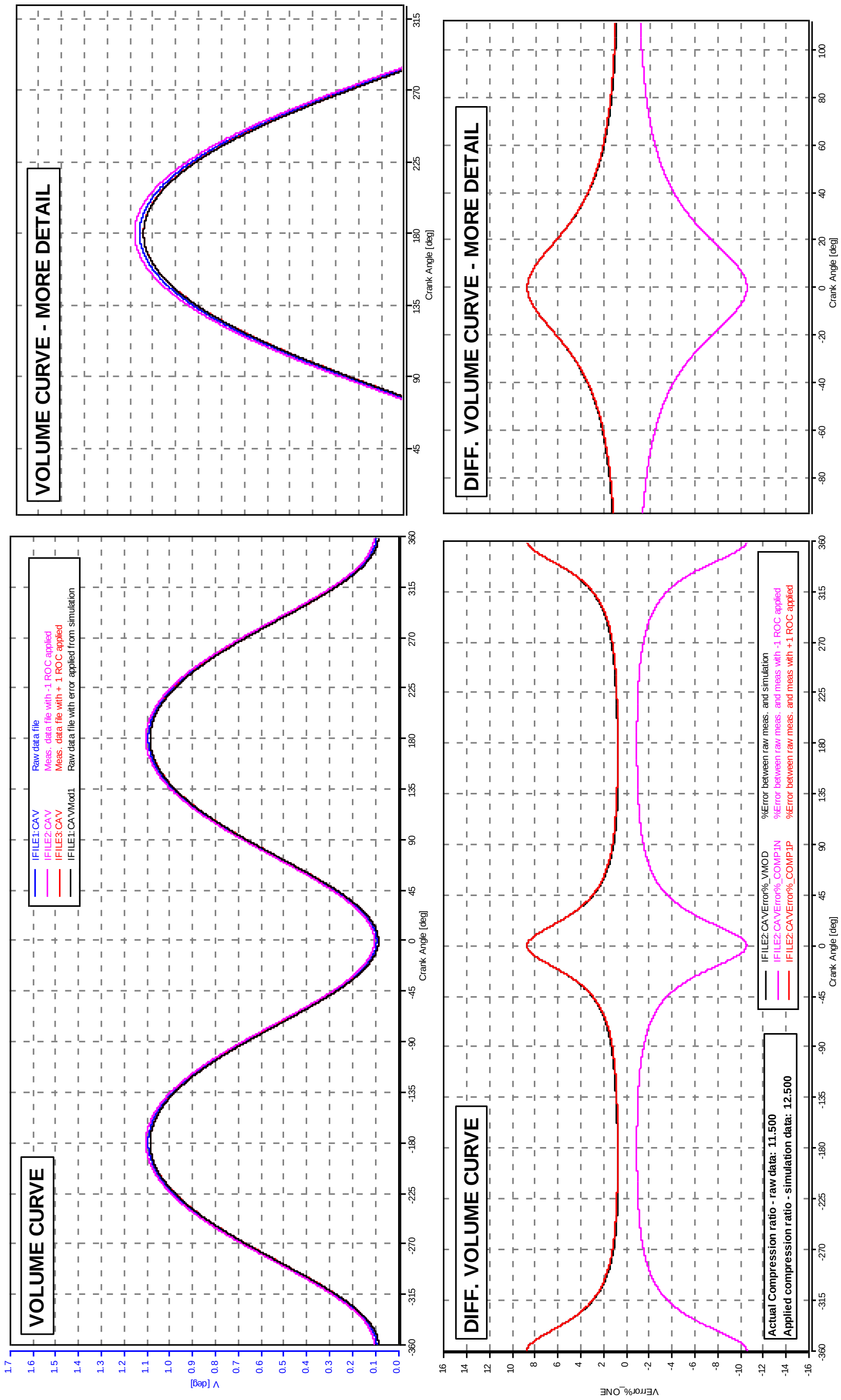


Figure 5.36: Plus one ROC applied to simulation data

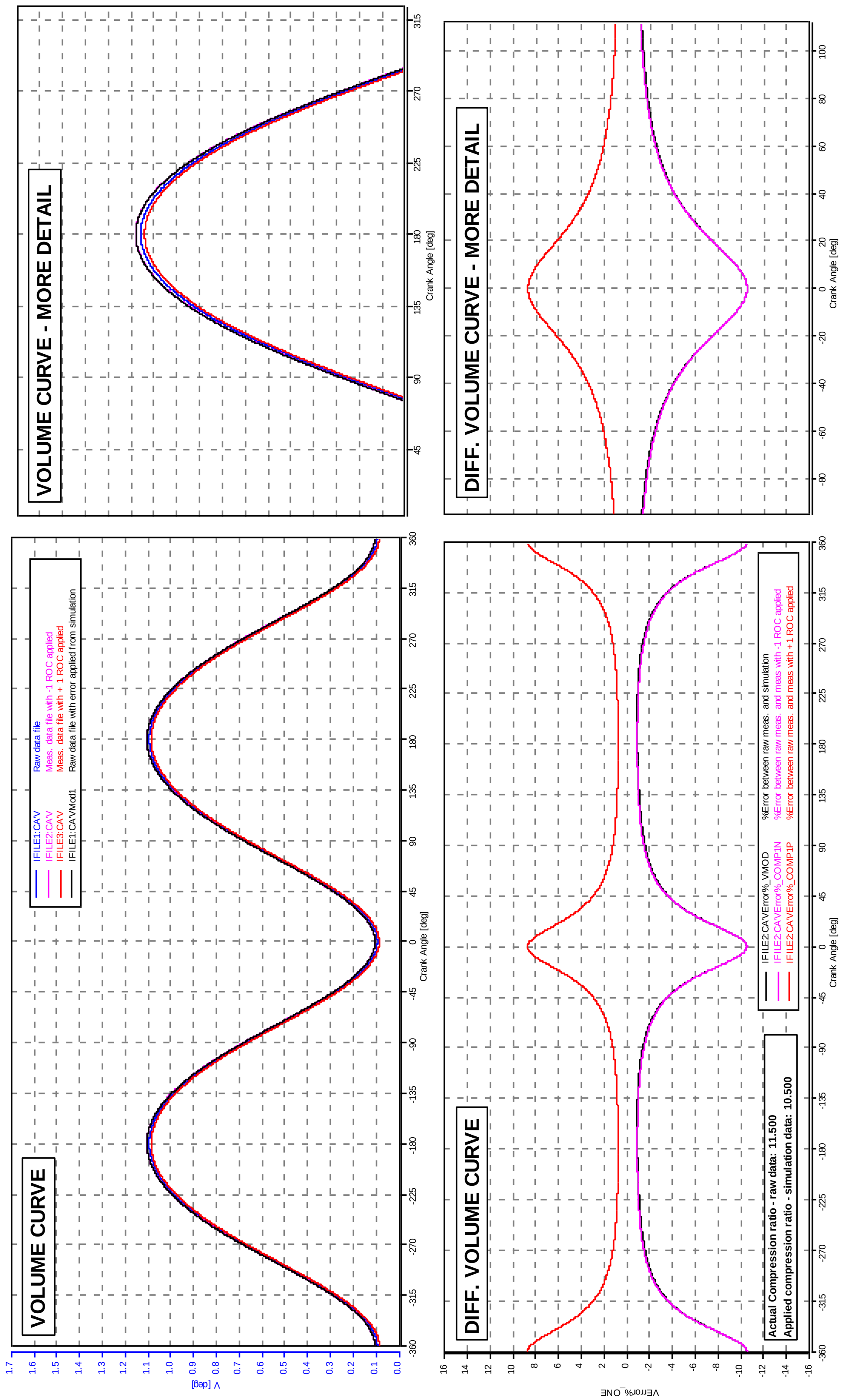


Figure 5.37: Minus one ROC applied to simulation data

These diagrams illustrate clearly the excellent correlation between data with simulation induced errors, and data with actual, applied errors. Note that for volume related curves, cyclic variation and variability are not a consideration as the curve is calculated from the geometry of the engine and the crank position; it is therefore not subjected to variability which is inherent in the combustion process.

5.4 Summary

In this section, result data generated by the developed simulation environment has been evaluated. This data has been modelled to provide sensitivity analysis functions for the 4 main error stimuli under investigation. The quality of the models achieved was very high, and these models were compared with verification data generated by alternative measurement designs, as well as actual measured data from a physical test with artificially induced errors.

The models which were generated show clearly which results are sensitive to what stimulus, in addition, the model based approach allows the interactions to be easily observed. This will form the basis for the further work needed to identify useful results that can be used to define critical aspects of data quality.

The model based approach, in conjunction with automation, was very useful with respect to the efficiency gain - in being able to run measurement procedures, in seconds, with a high degree of repeatability and reliability. It is often the case that with repetitive measurement sequences, there is a high risk of error created by complacency of the operator due to the boring nature of a task that needs repeating over and over.

In summary, at the end of this section, it is possible to say that a model based sensitivity analysis method has been successfully defined and executed, which has produced data that clearly shows the interaction and response of the output results, compared to the four main input stimuli. This would facilitate the process of defining which results are most useful and how they can be applied for data quality metrics.

6 Discussion and conclusions

In this section, the outcomes will be reviewed and discussed with respect to the targets achieved. Further work and direction for this work will be suggested and the less successful aspects will be discussed in terms of lessons learned and improvements that could be made. The overall output will be reviewed in terms of the results gained, and the conclusions based on the data that has been gathered.

6.1 Selection of the metrics and variations

Within this overall project there was a stated goal – to be able to define some quantitative metrics or performance indicators that could be used to assess the status of a combustion pressure measurement system (with respect to being able to produce quality data). In addition, it was suggested that metrics could be developed to assess objectively the quality of actual measured data, in a post-processing activity, thus facilitating an inexperienced person the ability to assess combustion pressure measurement data, with little pre-knowledge of data quality or assessment methods for this type of data. The former requirement could form the basis of a condition monitoring system for this measurement application. Whereas the latter would help in identifying low quality data and which aspect of the data is compromised (in order not to completely lose all value from the data).

In the first instance the typical problems encountered within the scope of combustion measurement data quality were discussed generally. In order to provide a realistic boundary for this work, and to provide some focus for the thesis, the author decided to concentrate effort on specific aspects of combustion measurement system parameterisation, which cause the greatest problems in practice. This was qualified by the authors experience working with many users of combustion measurement systems, both experienced and inexperienced. It was suggested that 80% of errors in combustion measurement data relate to four main aspects of the measurement system set-up, these being, scaling errors, phasing errors, process definition (polytropic) errors and compression ratio errors. Part of the justification is that the former two errors are dynamic in nature (as is the measurement) and are hence difficult to identify. The latter two are static errors, but are very difficult to establish accurately when compared to other static parameters which can be 'measured' – for example, engine geometry. This was a reasonable approach and if positives outcomes could be achieved, it was clear that this work would have value to the community of users and specialists, as well and generally in the industry.

6.2 Review of the process

The process and tools for the exercise provided an effective and efficient way of producing data with artificial errors, and then providing a platform on which to evaluate the required output (responses versus variation). The choice of commercially based tools means that the work done can be easily exported into an operational, commercial environment and this option will be explored post-study. Using standard file formats, in conjunction with graphical based environment, allowed rapid development and analysis of metrics. The simulation environment proved an effective way of taking measurement data and introducing the appropriate errors. This was a very time-efficient method of producing the required data sets for the study. In addition, any measurement data could be imported, modified and analysed easily. The overall process of developing a simulation environment, creating data sets with errors, analysing and comparing with real error data proved an efficient method for producing the required sensitivity analysis.

The choice made to exploit the strengths of commercially based tools proved a successful approach. Many commercial tools have powerful interfaces and programming capability. It is often the case however that many users only use approximately 10% of the total capability of the software. In this case, many of the inherent features of the software chosen were fully utilised. The advantage of this approach is a stable, reliable platform on which the required methods and approaches can be used and encapsulated. From this, it is easy to port the IP (Intellectual Property) into other commercial tools and environments; this would be much more difficult if a lower level programmatic approach had been employed.

6.2.1 Automation approach

The decision to use an automated procedure was driven by the fact that using this concept to create and store test data provides an increase in efficiency and in general, an increase in data quality (as the less manual intervention required improves repeatability). However, in this case, the efficiency aspect has a reduced impact due to the factor of working in a simulation environment. The reason being is that executing a test in simulation, in this instance, could be completed very quickly; also the test sequence was relatively short, and the calculations not computationally intensive (when compared to CFD or FE analysis).

The latter benefit of automation, with respect to repeatability of testing sequences, and the subsequent effect of the increase in data quality is much more relevant in this instance. Using an automated script to read in and execute the test plan had a considerable effect with respect to consistency of the data. This approach facilitated each test being reliably executed, according to the required DoE test plan, with the same results (and calculation methods) being used in each case. User interaction was minimised, only selection of the DoE plan and file path/name for the data file were input. Hence, repeatability of process and method could be almost guaranteed. The advantage was that many data files could be created, for analysis and comparison. A large number of results could be accumulated, allowing a good cross section of scenarios for comparison and validation of the developed metrics.

In general terms, an industry 'rule of thumb' suggests that automation needs to bring a time saving factor of ten or greater, in order to justify the disruption of implementing automation in a given environment.

6.2.2 Model based approach

The use of an experimental test plan and subsequent model based approach for analysis of result sensitivity proved to be a very successful approach. Using a DoE (Design of Experiment) method, the number of test points could be reduced considerably. As an example, when creating test data, a sequence with 625 points was completed in approximately 3 seconds, using a DoE design to reduce the measurement points to less than 100 meant that a data set for modelling could be gathered in 0.5 seconds – approximately one sixth of the time, this is not a particularly useful time saving in this instance. However, it is still a significant factor as there were many data sets to process. If a physical test environment is used then this time saving factor would be even more significant. A critical factor was the DoE design, a number of variants were considered, but as the responses characteristics could be considered somewhat predictable. A standard, well established approach of using the D-optimal design in conjunction polynomial based models was initially used. This provided good quality model results, and the methods mentioned previously used to optimise the creation of data, meant that many data sets could be quickly generated, modelled, analysed and compared.

During the development process, in addition to the polynomial models that were used, experiments were carried out using the 'automatic' model generation mode that became available in the Cameo software (Since V2013 R2). This allowed the utilisation of more complex model types (Intelligent Neural Networks using radial basis functions). The performance of this automatic model selection proved to perform excellently, and was found to produce very high quality models such that very tight tolerances could be used to narrow down the choice of the metrics for analysis. The automatic mode was eventually chosen as the preferred approach to model selection and creation.

6.2.3 Data analysis and verification

It was extremely important to continuously verify the data used for analysis and selection of the metric right throughout the process. Initially, measured data files were selected for good quality via analysis of averaged curves, and statistics of standard result values (in particular standard deviation of coefficient of variance). This provided an initial feeling on the quality of the data prior to error inducement and modelling. In addition, raw data curves were randomly 'spot checked' for noise and obvious errors – in particular those errors which are the subject of variation in this work. This was a manual approach, using data from many different sources, which provided data for different engine types (gasoline and diesel), at various different operating conditions (motored, idle and loaded).

These qualified data sets were then used in the automation script to generate the result data sets for modelling. Using the built in raw data analysis features in the Cameo software to detect outliers and 'bends' in the data was useful, but due to the nature of the data (i.e. from simulation), in general, it had very few errors when compared to data from a physical test subject. However, a particularly useful step was to use two designs in succession for gathering the data. This created data for model training, and another data set for verification. By using D-optimal design to collect data, then a SOBOL design to create a significant number of additional measurement points, a high level of confidence could be gained in the model when this additional data was used for verification. The collected verification points were pseudo-randomly distributed and hence, where good correlation existed, these measurements were an excellent reference for model quality. In normal measurement scenarios, the number of verification data points is limited in order to keep the total number of measurements needed within a manageable range (in order to support the general principle of using a model based approach to reduce the measurement time). Based on this model training and verification procedure, it was possible to define very tight tolerances for model quality. This meant that it was possible to really focus on the results which had excellent quality models. Thus, a high level of confidence could be felt in using these models and this approach, in order to define which results gave good response to error stimulation.

As an additional, final step, it was deemed necessary and appropriate to 'prove' the model based information and simulation data with real measurement data. For this, it was decided to focus on comparing averaged, measured curves with the simulation derived counterpart. A test plan was defined and executed that would produce errors at each extreme, boundary condition, as well as the centre position which is a no-error condition. In the test plan, the measurements were executed in such a way the no-error measurement condition was checked before and after each set of measurements. In addition, a pre and post-test physical checking procedure ensured that the process of gaining the measurement data was robust, and could be considered reliable. The comparison of the data sets showed that the simulation environment performed very well in being able to produce data sets with appropriate errors, from any given file. This meant that a wide range of samples could be taken from engines in many different operating conditions, in order to fully evaluate the response of the chosen metrics across many different scenarios. The method of using curves as opposed to results for the comparison was considered appropriate as the results are always derived from the measured or calculated curves in some way. Hence focusing on the appropriate 'curves' that are sensitive to the appropriate error stimuli proved to be an appropriate methodology – and provided a satisfactory result and level of confidence in the data.

6.3 Summary and outlook

In summary, it was possible to define a number of key result parameters, using a model based approach, which had particular sensitivity to those errors in combustion pressure data, which were proposed as important within the scope of this project. Specifically, the errors which cause the greatest number of problems in a typical measurement task (according to the authors experience). The metrics were narrowed down and evaluated, with respect their response to error stimulation, as well as any interaction effects. The models that were built from simulation data were used to evaluate the result data, each error case that was considered is discussed below:

6.3.1 TDC based errors

TDC errors are the most common and troublesome source of error. The reason being is that in order to gain an effective, reliable TDC position signal, an engine angle encoder is required to be fitted to the crankshaft. An operating engine is a particularly harsh environment for any measurement equipment, but, the encoder is mounted directly on the engine and is subject to all vibration and temperature extremes. It is therefore often the case that TDC could be 'lost' during a measurement due to encoder failure. In addition, incremental encoders are exclusively used in combustion measurement. It is therefore a necessary pre-requisite that before a measurement, TDC must be defined. This could involve a number of methods and procedures that, if not carried out in a repeatable and traceable way, will lead to errors and variations that may be difficult to identify problem root cause. TDC errors are poignant due the fact that accurate TDC is difficult to gain, and then maintain in a typical test environment. As well as the fact that a small error in TDC, produces a significant error in a calculated result. Within the scope of this work, we examined the responses of a number of results with respect to TDC errors. However, it was clear that the only results that had any useable sensitivity to TDC errors were those which were based around IMEP based results. From the research carried out it is clear and well known that these results are very sensitive to IMEP, and hence could be a good indicator of TDC based errors, this was also shown clearly in the model based data analysis. However, it was found that it would not be possible to derive a TDC error reliably, without having a reference point to compare against. That is, it would not be possible, from a single cycle, to detect a TDC based error from an IMEP based value. The reason is that there are too many other factors that can affect the IMEP, not just the TDC. This was a disappointing outcome but based on the authors experience, and the literature search carried out, not unexpected. None of the other chosen metrics had any significant response to TDC variation that could be isolated as useable, so this proved that there was no interaction between the results either. In summary, IMEP results could be used as an error indicator for TDC but some application or test specific reference point must be defined in order to detect a drift away from the correct TDC value. This could be gained via a 'calibration' test – i.e. a measurement routine providing a reference point data set, Or, via comparison of data sets over time, for a specific operating condition, in order to detect an error (either as a step or drift). The main problem with this approach is the fact that it cannot be applied to already measured data (where, in a typical scenario, no calibration or history data is available).

6.3.2 Pegging or zero-level errors

Pegging errors stimulated some responses in all the results, except those based on IMEP. So it was necessary to decide which result has the most suitable and reliable response, and was also less influenced by any other error stimulation. On this basis, the ROHR and Polytropic based results were rejected - although they both had sufficiently sensitive output relative to pegging error stimulation. The output was not exclusive, for Polytropic results, a similar magnitude output could be seen from TDC error stimulation (but opposite polarity), this meant that there could be some interaction if both errors exist, creating a masking effect. Heat curve (ROHR) results had a more significant response to pegging errors, some of the other results created a similar response with lower magnitude, hence the problem of interaction and masking could also occur.

The most promising result group in respect to pegging errors was the process constant (PV^n) based results. These showed a very positive and linear response to pegging errors. This means that via a simple threshold or boundary setting on the result, a pegging error could be detected from this result alone, and from a single cycle of data. This was a successful outcome but there were some caveats to be considered with respect to general application. When testing this result with various engine types and operating conditions, a reliable response was seen but somewhat specific to engine type. That is, it would not be possible to define a single threshold or boundaries that would be appropriate for all engines. Clearly this result is sensitive to volume and pressure difference, as well as the defined process constant, and these vary from engine to engine of course. Therefore, it would be suggested that some kind of calibration of the threshold values would be necessary in order to make results derived from this calculation useable in practice.

6.3.3 Compression ratio errors

The compression ratio is a static error which will occur during the parameterisation of the measurement system. Normally, the information is given for this setting according the engine design geometry. However, it is often the case that the source of information is difficult to accurately trace, also, the measurement or derivation method can be impossible to establish. In addition, modifications made to the engine during the development process (e.g. fitting an in-cylinder transducer or changing a piston bowl design) can have a significant impact that is almost undetectable. The tolerance set for monitoring this error was quite small, but also realistic in order to make the evaluation a feasible prospect. From the data and modelling, it was clear that the result set with the most significant response sensitivity, was the ROHR based results group.

This therefore would have been a good prospect for detecting compression ratio errors apart from the fact that a TDC based error seemed to produce a similar, linear response to error stimulation (although of a lower overall magnitude). This therefore creates the situation that it would not be possible to clearly identify what error caused the problem and ultimately stimulated to the ROHR result (i.e TDC or compression). Hence using this result, in isolation, to detect this error state was not possible. It could therefore be suggested that detecting a compression ratio parameterisation error, from a measured pressure cycle or derived result, would not be possible in a reliable way.

6.3.4 Polytropic definition errors

Definition of the polytropic parameter is used in several derived curves and calculated results (mainly ROHR, and other thermodynamic related calculations). The problem is that it can be very difficult to choose a single, representative value, due to the complex combustion modes in a modern engine. It is also the case that the polytropic values vary throughout the cycle, such that a single value may not be at suitable. In most cases a single value is used within the measurement system as a global parameter. But it is a source of error when defined incorrectly. However, it is often a hidden error as if the wrong value is defined in a test, as long as the same value is used consistently throughout the test series, then, for relative based measurements (most often the case) it can be undetected. Of all the error scenarios that have been suggested, this one has the least impact and causes the least problem in service. During the testing and evaluation, it was clear that using the result groups defined, it would be practically impossible to detect in isolation and polytropic based error from the measured curve/results alone. None of the result groups used showed any real sensitivity to polytropic based error stimulation. This was a disappointing outcome which would promote the need for further investigations that would be required (outside the scope of this work)

6.4 Conclusion

This work used a unique approach in order to be able to predict the behaviour of newly developed calculated results, with respect to their response to error stimulation, and evaluation of this response with respect to combustion pressure measurement data quality issues. The simulation environment, automation of data collection, modelling and analysis proved to be a robust and efficient prototyping environment in order to be able to carry out the evaluation efficiently.

Although the responses of typical results are relatively well known, to the authors' knowledge, this approach to modelling these responses in order to evaluate magnitude and interactions is unique. It is foreseeable that this approach could be very useful; not only for developing more metrics, but also to gain a greater understanding of the interactions between results during normal and abnormal combustion conditions. In addition, the view on the data (as a model) is very useful for teaching and learning environments where it is important to understand such reactions and interactions.

One factor within this work that should not be underestimated is the standardisation approach. Within this work standard software tool platforms were used, in addition, standard procedures for acquiring measurement and validation data sets were also proposed. This 'standardisation' approach is a key driver for efficiency and quality in Industry and it is therefore pertinent that the same mentality should be used in a research project. In particular, with a project such as this where the outcome could have a commercially viable concept. A defined standard procedure (as discussed in Chapter 4 and applied within this project) shows that consideration of "what to measure?" as well as "what are the effects?" and these factors are equally important as they are underpinning drivers and enablers to process, and subsequent data quality.

In order to focus the project, boundaries were set with respect to examining specific result groups. The actual outcome of producing a single metric for data quality was not achieved but this is intended as a further extension of the project. This would be done in conjunction with additional modelling approaches for comparison, as well as analysis of how this metric would perform with transient data, in particular exploring the boundaries of operating limits with respect to accuracy and repeatability.

This work is unique in its approach and provides an excellent foundation for further research in this area, which is of great value to industry and the academia, as one of the greatest challenges in combustion measurement is gaining accurate, repeatable data.

6.5 Further work and recommendations

The outcome of this thesis is that using the suggested approach, metrics were identified that could be used to assess combustion measurement data quality – taking into account some considerations.

The performance of the metrics as researched had a mixed success, however there are some clear considerations that should be noted.

- Although the performance of the results, standalone, had a limited success. It would be possible to gain a better depth and quality of metric performance if they could be combined and used together to identify errors of a specific type. This would give some level of plausibility and allow a degree of freedom for tuning the response in more depth, for specific applications.
- The goal was to derive metrics that could identify the given problems from a single cycle. This was found to be not feasible in most cases. However, statistical evaluation of a larger data mass, gained historically, would be a feasible approach and this could be built into any defined measurement routine or process. A particular area would be TDC related errors. The IMEP based results could be used in this way to detect TDC related errors. A simple routine could be combined with the TDC calibration procedure to give baseline data. In addition, IMEP from specific fired operating conditions could be gained and recorded easily for the purpose of tracking data quality over a project basis (i.e a control chart).
- The methodology to build up the simulation environment and use a model based approach proved to be robust. This means that the same

technique and system could be used to research any further results very easily. More calculated results could be easily ‘rapid prototyped’ and tested for further research work.

In general, the project could be extended further to add more value to the overall concept in the following ways:

- Although a significant number of results were developed and considered, now the working environment is available, many more could easily and quickly be created and tested. This would be a suitable extension for the project. To identify further problem issues and investigate appropriate metrics – in particular, in the area of transducer measurement quality. Metrics which could identify common transducer related problems, like thermal shock and drift.
- A concept could be defined for an approach to combining the metrics and data to provide a single, discrete value to identify measurement data problems – this was discussed at an earlier stage in the project but time did not allow taking this approach further. It is suggested that it could be possible to use results in combination, for example, to define a pegging error by combining ROHR and PV^n with appropriate combinational logic, or with a simple state machine to give a qualified output that the error has occurred. A single combined metric as a data quality warning would be very useful to inexperienced users (analogous to the malfunction indicator light fitted in every light vehicle with On-board diagnostics).
- Another possibility would be to create a single measurement quality rating value. A dimensionless unit to give an overall quantitative indicator of the measurement quality of any particular measurement data. This could be developed as a response to inputs from the other metrics, these could have weighting factors associated, or a neural-network could be used to combine the inputs in order to provide a self-adapting output for measurement quality. It would be anticipated that this metric could be used during, or after the measurement.

- Alternative modelling approaches could be employed for more complex functions. Although the Neural-Network and advanced polynomial approaches in this study performed well. It would be interesting to compared the models with alternative, newer models (Statistical Machine learning, Gaussian modelling). Generally, this model type can produce high quality models and response surfaces from a relatively simple SOBOL design. In addition, this design can be used such that it provides verification as well as training data. This would simplify the design process, as well as the data collection approach.

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Appendices

Appendix A – Program code for pressure curve adjustment value

```
//_comment = Measured data manipulation for testing
//_comp = Alg.|PMod (A), VMod (A)
//_src1 = SourceSignal|PCYL
//_defnames = PMod, VMod
//_frm = Start of Calc.[deg CA]
//_to = End of Calc. [deg CA]
//_int = Calc.Resolution [deg CA] (0=Auto)
//_n = Polytropic Index
//_offs = Offset
//_len = Conrod length
//_strk = Stroke length
//_cmpr = Compression ratio
//_yoff = Pressure scale offset value (bar)
//_xoff = TDC offset value (degCA)

arg _src1, _comp=0, _frm=-360, _to=360, _int=0.5, _n=1.3, _offs=0,
_len=150, _strk=86, _cmpr=12, _yoff=0, _xoff=0

//This section calculates modified volume table
R = _strk/2  //Radius = Stroke/2

dltOT = Asin(_offs/(_len+R))

dltUT = Asin(_offs/(_len-R))+ 180

Hw = sqrt((_len+R)*(_len+R)-_offs*_offs) - sqrt((_len-R)*(_len-R)-_offs*_offs)

rangedDS = range(_src1,_frm,_to,_int)

phi = xds(rangedDS)

f= _offs- R*sin(dltOT+phi)

x= sqrt((_len+R)*(_len+R) - _offs*_offs ) - R*cos(dltOT+phi) - sqrt(_len*_len -
f*f)

Hw = sqrt((_len+R)*(_len+R)-_offs*_offs) - sqrt((_len-R)*(_len-R)-_offs*_offs
)

Vnorm = x/Hw

Vc = 1/(_cmpr - 1)

VOL = Vnorm + Vc

Va = create(phi,VOL)
```

```
Va.SetFormat(2)

//This section calculates the modified pressure curve
P=range(_src1,_frm,_to,_int)
V=range(Va,_frm,_to,_int)
Pa = P + _yoff

if _comp = 0 then
return Pa
else
returncreate(xds (V)+_xoff,V)
endif
```

Appendix B – Program code for measurement automation

```
//
============================================================================
// ==== SECTION FOR PERSONAL DEFINITION

fAliasR = "ASCII1"// ALIAS of Reference-File
fAliasI = "IFILE1"// ALIAS of iFile
FileExtension = ".txt"

App = GetApplication()
MyFile = App.FileDialog(%MyDataDir, "*" + FileExtension, "Export.txt", "Export Calculation Results", "Save as")
ifMyFile = ""thenreturn 0
ifStrSearch(MyFile, FileExtension) = 0 thenMyFile = MyFile + FileExtension
iExist = App.FileExists(MyFile)
whileiExist = 1
   Choice = MsgBox("File already exists! Do you want to overwrite?", 4, "Information")
if Choice = 7 then
MyFile = App.FileDialog(%MyDataDir, "*" + FileExtension, "Export.txt", "Export Calculation Results", "Save as")
ifMyFile = ""thenreturn 0
ifStrSearch(MyFile, FileExtension) = 0 thenMyFile = MyFile + FileExtension
iExist = App.FileExists(MyFile)
else
iExist = 0
endif
endwhile

// declare uservariables and their corresponding datasets (Syntax= Uservariable,dataset)
UserVarDefinition = {   "%Comp,D'%Comp", \
"%Poly,D'%Poly", \
"%Pegging,D'%Pegging", \
"%TDC,D'%TDC" \
                }


// declare information, which should be exported. either define uservariable or dataset-name (which will be taken from the iFile then)
ExportInformation = {   "%Comp", \
"%Poly", \
"%Pegging", \
"%TDC", \
"MSC'Cmpratio", \
"MSC'PolyVal", \
"MSC'Poffs", \
"MSC'Voffs", \
"VAL'CG_IMEP1", \
```

```
"VAL'CG_IMEP_Error1", \
"VAL'CG_IMEP_mod1", \
"VAL'CG_PMEP1", \
"VAL'CG_PMEP_Error1", \
"VAL'CG_PMEP_mod1", \
"VAL'Error_IMEP_TDC_shift1", \
"VAL'IMEP_PCYL_TDC_mod1", \
"VAL'INTHR_Slope_15BTDC1", \
"VAL'INTHR_Slope_45ATDC1", \
"VAL'MBF100%1", \
"VAL'MBF90%1", \
"VAL'MBF_SUB1", \
"VAL'PolyInt_EX1", \
"VAL'PolyInt_IN1", \
"VAL'POLYVAL3090ATDC1", \
"VAL'POLYVAL9030BTDC1", \
"VAL'POLYVAL_100BTDC1", \
"VAL'POLYVAL_30BTDC1", \
"VAL'POLYVAL_SUB1", \
"VAL'PVn135BTDC1", \
"VAL'PVn90BTDC1", \
"VAL'PVn_sub1" \
                }


// ==== SECTION END (do not change code below)
//
============================================================
==============


sAliasR = SelFile(fAliasR)
sAliasI = SelFile(fAliasI)

ifUserVarDefinition.Count() = 0 thenreturn 0  // if no variables defined, script
will abort here
UserVarDefinitionDS = StrTokenize(UserVarDefinition.y[33], ",")
LoopCounter = ds(fAliasR + ":" + CStr(UserVarDefinitionDS.y[42])).Count()

fori=1 toLoopCounter

for u=1 toUserVarDefinition.Count()
UserVarDefinitionDS = StrTokenize(UserVarDefinition.y[u], ",")
SetUserVar(UserVarDefinitionDS.y[33], ds(fAliasR + ":" +
UserVarDefinitionDS.y[42]).y[i])
nexti


// recalculate IFILE
sAliasI.Update()
```

```
ResetFormula()

// Build "LINE's" of information, which will be exported
LineData = ""
LineHeader = ""
LineUnit = ""
DataSeperator = ""
for n=1 toExportInformation.Count()
ActValue = ExportInformation.y[n]
ifStrCopy(ActValue,1,1) = "%"then
LineHeader_Act = StrCopy(ActValue,2)
UserVarDefinitionEntry = Reduce(UserVarDefinition,
StrSearch(UserVarDefinition, ActValue))
UserVarDefinitionEntryDS = StrTokenize(UserVarDefinitionEntry, ",")
LineUnit_Act = ds(fAliasR + ":" + CStr(UserVarDefinitionEntryDS.y[42])).Unit
LineData_Act = GetUserVar(ActValue)
else
TmpDS = ds(fAliasI + ":" + ActValue)
LineHeader_Act = TmpDS.Name
LineUnit_Act = TmpDS.Unit
LineData_Act = TmpDS.y[33]
endif

if n > 1 thenDataSeperator = ";"

LineHeader = LineHeader + DataSeperator + LineHeader_Act
LineUnit = LineUnit + DataSeperator + LineUnit_Act
LineData = LineData + DataSeperator + LineData_Act

next n

// now export result
ifi=1 then
WriteLn(MyFile, LineHeader, 0)
WriteLn(MyFile, LineUnit, 1)
endif
WriteLn(MyFile, LineData, 1)

nexti


TraceInfo("New file created and exported to '" + MyFile + "' finished.")

return 0
```

Appendix C – Table: derived curves and results used for an initial feasibility test to evaluate sensitivity of result outputs

Calculation	Output type	Name
CG_IMEP1	Cyclic result	IMEP from Formula
CG_IMEP_Error1	Cyclic result	Error % between IMEP from modified and unmodified pressure curve
CG_IMEP_mod1	Cyclic result	IMEP from formula, derived from modified curve
CG_PMEP1	Cyclic result	PMEP from Formula
CG_PMEP_Error1	Cyclic result	Error % between PMEP from modified and unmodified pressure curve
CG_PMEP_mod1	Cyclic result	PMEP from formula, derived from modified curve
Error_IMEP_TDC_shift1	Cyclic result	% Error IMEP derived from curve with TDC shift applied to pressure curve, compared to unmodified value
IMEP_PCYL_TDC_mod1	Cyclic result	IMEP derived from curve with TDC shift applied to pressure curve
INTHR_Slope_15BTDC1	Cyclic result	Gradient of Intergral heat release at 15 degrees CA before TDC
INTHR_Slope_45ATDC1	Cyclic result	Gradient of Intergral heat release at 45 degrees CA after TDC
MBF100%1	Cyclic result	Angle of 100% mass burned fraction
MBF90%1	Cyclic result	Angle of 90% massburned fraction
MBF_SUB1	Cyclic result	Crank angle between 100 and 90% mass burned fraction
PolyCurve_mod_Int30BTDC1	Cyclic result	Intergral curve of rectified poytropic curve, value at 30 degrees before TDC, derived from modified curve
PolyCurve_mod_Int60ATDC1	Cyclic result	Intergral curve of rectified poytropic curve, value at 60 degrees after TDC, derived from modified curve
PolyCurve_mod_Int_SUB1	Cyclic result	Distance in crank degrees between intergral value of rectified poltropic curve, values at 30BTDC and 60ATDC
PolyInt_EX1	Cyclic result	Integral value of rectified polytropic curve between -2 and 0 degree CA
PolyInt_IN1	Cyclic result	Integral value of rectified polytropic curve between 0 and 2 degree CA
POLYVAL1_SUB1	Cyclic result	Subtraction of values PolyInt_IN1 and PolyInt_EX1
POLYVAL3090ATDC1	Cyclic result	Polytropic curve, derived from TDC shifted curve applied to pressure curve, polytropic value calculated between 30 and 90 degrees CA after TDC
POLYVAL9030BTDC1	Cyclic result	Polytropic curve, derived from TDC shifted curve applied to pressure curve, polytropic value calculated between 90 and 30 degrees CA before TDC
POLYVAL2_SUB1	Cyclic result	Subtraction of POLYVAL3090ATDC1 and POLYVAL9030BTDC1
POLYVAL_100BTDC1	Cyclic result	Value of rectified, polytropic curve at 100 degrees before TDC
POLYVAL_30BTDC1	Cyclic result	Value of rectified, polytropic curve at 30 degrees before TDC
PVn135BTDC1	Cyclic result	Value of PVn, from modified curve at 135 degrees before TDC
PVn90BTDC1	Cyclic result	Value of PVn, from modified curve at 90 degrees before TDC
PVn_sub1	Cyclic result	Subtraction value of PVn135BTDC1 and PVn90BTDC1
Pcomp1	Crank angle curve	Extrapolated compression curve

Calculation	Output type	Name
Pcomp_mod1	Crank angle curve	Extrapolated compression curve derived from the modified pressure curve
PComp_mod_D1P1	Crank angle curve	1st derivative of extrapolated compression curve derived from the modified pressure curve
PComp_mod_D2P1	Crank angle curve	2nd derivative of extarpolated compression curve derived from the modified pressure curve
PCYL_AVG1	Crank angle curve	Average cylinder pressure curve envelope
PCYL_Mod1	Crank angle curve	Modified, Average cylinder pressure (TDC applied to volume, pressure offset applied to pressure curve)
PCYL_TDC_mod1	Crank angle curve	Average cylinder pressure, TDC adjusted on pressure curve
PCYLc1	Crank angle curve	Average cylinder pressure curve (TDC shift and pressure offset applied to pressure curve)
PCYLc_PolyCurve_mod1	Crank angle curve	Polytropic curve derived from PCYLc1
PCYLc_PVn1_mod1	Crank angle curve	PVn curve derived from PCYLc1
PCYLc_PVn2_mod1	Crank angle curve	PVn curve derived from PCYL_AVG and V (cross-check)
PDiff1	Crank angle curve	Pressure difference due to combustion alone from average pressure and volume curve (unmodified)
PDiff_mod1	Crank angle curve	Pressure difference due to combustion alone from average pressure and volume curve which are modified (offset applied to pressure and volume curves)
PolyCurve1	Crank angle curve	Polytropic coefficient curve from PCYL_AVG
PolyCurve_mod1	Crank angle curve	Polytropic coefficient curve from pressure curve with pressure and volume shift applied to respective axis
PolyCurve_mod_abs1	Crank angle curve	Rectified polytropic coefficient curve from channel PCYLc_PolyCurve_mod1
PolyCurve_mod_Int1	Crank angle curve	Integration of PolyCurve_mod_abs1
PRatio1	Crank angle curve	Difference curve between combustion and extrpolated motor curve, derived from PCYL-AVG
PRatio_mod1	Crank angle curve	Difference curve between combustion and extrpolated motor curve, derived from pressure and volume modifed curves
PVn1	Crank angle curve	PVn curve derived from average cylinder pressure curve
PVn_D1P1	Crank angle curve	1st derivative curve of PVn1
PVn_D2P1	Crank angle curve	2nd drivative curve of PVn1
PVn_mod1	Crank angle curve	PVn curve derived from pressure and volume adjusted curves
PVn_mod_D1P1	Crank angle curve	1st derivative curve of PVn_mod1
PVn_mod_D2P1	Crank angle curve	2nd drivative curve of PVn_mod1
Th1_dq1	Crank angle curve	Rate of heat release curve, derived from PCYL_AVG
Th1_dq_mod1	Crank angle curve	Rate of heat release curve, derived from cylinder pressure with modified pressure and volume curves
Th1_Int1	Crank angle curve	Intergral of heat release curve, derived from PCYL_AVG
Th1_Int_mod1	Crank angle curve	Integral of heat release curve, derived from cylinder pressure with modified pressure and volume curves
VOL_Mod1	Crank angle curve	TDC shifted volume curve, from Average cylinder pressure dataset
Wiebe1	Crank angle curve	Weibe function, derived from average cylinder pressure dataset

Appendix D – Table: test point generated using D-optimal design

Test point	%TDC	%Pegging	%Comp	%Poly
[N]	[Deg_CA]	[bar]	[N]	[N]
1	0	0	0	0.025
2	2	5	-1.6	0
3	-0.05	-10	-1	0.025
4	2	-10	2	0.1
5	-2	10	2	-0.05
6	-0.8	10	1.6	0
7	-1.6	10	-2	0
8	1.2	-5	-2	0.05
9	-2	-10	2	-0.025
10	2	10	1.8	0.1
11	-1.2	5	1.2	0.05
12	-2	-10	-0.8	-0.05
13	0.8	10	-1.6	-0.05
14	0.8	-10	1.6	-0.05
15	2	10	1	-0.05
16	-0.8	-10	2	0.075
17	0.8	5	1	0.075
18	1.2	-10	0	-0.025
19	-1.6	0	-0.2	0.075
20	1.2	5	2	0
21	-0.4	10	-2	-0.025
22	2	-10	-1.8	-0.05
23	-1.6	-5	2	-0.05
24	-2	10	0.8	0.1
25	2	-10	-2	0.1
26	-0.15	10	2	0.1
27	-0.8	-5	0.4	0
28	-1.6	-10	-1.6	-0.025
29	-1.6	-10	1.6	0.1
30	-1.2	5	-0.8	0.1
31	-2	10	-1.6	0.05
32	-0.4	0	-1.6	0.1
33	1.6	-5	0.8	0.1
34	-2	-10	-2	0.1
35	1.6	-10	2	-0.05
36	-2	5	-2	-0.05
37	2	10	0	0.05
38	1.6	-10	-1.6	0.075
39	-2	-5	1.6	0.075
40	2	-5	-1	-0.025
41	1.6	5	1.6	-0.025
42	1.6	10	-2	0.1

Appendix E – Measurement procedure for validation data

Good quality dataset

Procedure as follows:

- Physical check as described above
- Ensure engine is a normal operating temperature
- TDC check - Carry out and verify correct TDC position (no fuelling, WOT if motoring via dynamometer)
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data

TDC error dataset

Procedure as follows:

- Ensure engine is a normal operating temperature
- TDC check - Carry out and verify correct TDC position (no fuelling, WOT if motoring via dynamometer.)
- In Indipar, subtract 2degCA from the TDC offset value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, add 2degCA from the TDC offset value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, return TDC offset value to the original value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data

Pressure scale error dataset

Procedure as follows:

- Ensure engine is a normal operating temperature
- TDC check - Carry out and verify correct TDC position (no fuelling, WOT if motoring via dynamometer)
- In Indipar, apply -2 bar offset on the pressure scale
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, apply +2 bar offset on the pressure scale
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, apply no offset on the pressure scale
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data

Polytropic error dataset

Procedure as follows:

- Ensure engine is a normal operating temperature
- TDC check - Carry out and verify correct TDC position (no fuelling, WOT if motoring via dynamometer)
- In Indipar, apply -0.01 offset to the global polytropic coefficient value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, apply +0.01 offset to the global polytropic coefficient value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, remove the offset to the global polytropic coefficient value
- Measure/save100 cycles of data at idle condition

- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data

Compression ratio error dataset

Procedure as follows:

- Ensure engine is a normal operating temperature
- TDC check - Carry out and verify correct TDC position (no fuelling, WOT if motoring via dynamometer)
- In Indipar, apply an offset of -1 to the global compression ratio value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, apply an offset of +1 to the global compression ratio value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data
- In Indipar, remove the offset to the global compression ratio value
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data

Test verification data

On completion of the above, remove all the applied offsets, reinstating correct parameters and repeat the procedure:

- Ensure engine is a normal operating temperature
- TDC check - Carry out and verify correct TDC position (no fuelling, WOT, if motoring via dynamometer)
- Measure/save100 cycles of data at idle condition
- Measure/save 300 cycles of data at 2000rpm/50% load
- Measure/save 100 cycles of unfired, motored data

Note:

The following file naming convention for each measurement data file was to be used:

- Metric/error state: Good1 (pre-test), TDC, Press, Poly, Comp, Good2 (post-test)
- Error offset: -2, +2, 0
- No. of cycles: 100, 300
- Operating condition: idle, load, motored

Separate each with an underscore, please use the file extension *.dat

For example, the measurement – Polytropic error, +0.01 offset, Measure/save 300 cycles of data at 2000rpm/50% load would be called:

Poly_+0.01_300_load.dat

Another example, the measurement – Compression ratio error, +1 offset, Measure/save 100 cycles of data at idle would be called:

Comp_+1_100_idle.dat

Another example, the measurement – Compression ratio error, -1 offset, Measure/save 100 cycles of unfired, motored data:

Comp_-1_100_motored.dat

This file naming convention was used in order that the measurement condition, for each file, was easily identifiable, just from the filename. Such that it was not necessary to actually open the file, to see what was contained, with respect to operating state during the measurement.

Appendix F – Measurement procedure for TDC calibration

- Warm up engine to normal operating temperature
- Carry out a TDC determination using motored pressure curve method
- During the TDC calibration, disable the fuel system, open the throttle valve fully
- If the procedure is carried out correctly, a TDC value and deviation statistic will be returned, please note the values and store the TDC
- If the measurement is not successful, the measured curve is not sufficient quality:
    - Repeat the procedure with increased charge amplifier gain and re-parameterise the input signal to improve digital resolution
    - Make sure fuelling is disabled, crank the engine to remove residual fuel in the cylinders
    - If possible, increase engine speed to dampen large speed fluctuations
    - Measure and examine the raw pressure signal, look for a smooth symmetrical curve

- Once a successful measurement has been made and stored, repeat the process again twice, note the standard deviation and the actual offset value in each case. The overall results should be repeatable over 3 successive measurements. Continue until this is achieved
- On completion of above, it can be assumed TDC has been successfully defined according to a standard procedure. This should now be recorded via saving of the parameter file (used for TDC determination, please save the setting used for the amplifier and input scaling, also note manually).
- Measure and save the motored pressure curve, using the above parameter set. Measure 100 cycle of data and save.